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DEEP BOREHOLE STRAINMETER TO MEASURE EARTH STRAIN

T. C. Moore, et al

Develco, Incorporated

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ABSTRACT

A highly sensitive multicomponent strainmeter has been designed for use in deep boreholes. A shallow-hole version of the deep-hole strainmeter was constructed and tested by operating it in a mine tunnel near the seismically active area around Mina, Nevada. The ability of the strainmeter to record tidal strains of approximately 1 x 10^{-8} in the horizontal direction and approximately 1 x 10^{-9} in the vertical direction has been demonstrated.

FOREWORD

The scientific direction for this work was provided by Dr. R.L. Kovach, Professor of Geophysics at Stanford University, and Dr. S. W. Smith, Professor of Geophysics at the University of Washington. The design and fielding work was performed by several members of the Engineering Department of Develco, Inc. as follows:

N. Delevaux	Instrument Assembly and Field Support
H. Feuss	Downhole Electronics Design
J. Klein	Wellhead Electronics Design
L. Orsak	Technical Direction
J. Yeatts	Instrument Mechanical Design

In addition, staff members of the US Army Corps of Engineers, Waterways Experiment Station at Vicksburg, Mississippi, and Engineering Division, Foundation and Materials Branch, at Mobile, Alabama, provided valuable support in the development of grout and installation methods, as well as for the borehole preparation and installation. We also wish to thank Dr. A. Ryall, Mr. W. Nicks, Mr. I. McPherson, and others of the University of Nevada Seismological Laboratory for their cooperation and assistance during the installation and operation of the strainmeter. The project direction and review provided by Lt. Col. D.W. Klick and Mr. W.J.Best of the Air Force Office of Scientific Research was also a significant contribution to the program.

T. C. Moore
Program Manager

L. H. Borden
Principle Investigator

CONTENTS

1. INTRODUCTION

A major limitation in earth strain measurements is the background noise present at or near the surface where most such measurements are currently made. Highly fractured rock found at near-surface sites, including deep tunnels and mines, presents special problems in nonelastic behavior due to slip in response to transient waves. Topographic irregularities can introduce noise to depth comparable to the mean amplitude and wavelength of the surrounding terrain by means of thermoelastic effects, wind stresses and water table fluctuations.

For strainmeters installed in mines or tunnels extreme care must be taken to minimize the undesirable noise produced by air circulation and changes in barometric pressure and temperature. A disadvantage of conventional installations in mines and tunnels is that the location of the strain installations is dependent on the availability of an abandoned mine or tunnel. Strainmeters have been installed in shallow trenches but the perturbing effects of local geologic and tectonic conditions are difficult to ascertain.

In order to avoid such near-surface effects and obtain accurate, repeatable strain information, it is necessary to perform the measurements at a considerable depth below the earth's surface. To meet this objective, a new type of strainmeter was designed and constructed for installation in a small diameter borehole. Measurements are made for three horizontal and one vertical component of earth strain using a six-inch-baseline quartz rod extensometer-type strain sensor. To achieve operational and measurement redundancy, both an extra horizontal component and a vertical component were included in the first borehole strainmeter and the design provides for the use of up to two full sensor groups if desired. The strain sensors are capable of resolving strain changes of less than 10^{-9} and have a full scale capability of 10^{-5}. The strainmeter design permits the instrument to be installed to depths of several throusands of feet, solidly coupled to the walls of the borehole by grouting, and reliably operated over extended time periods within the environmental constraints of temperature and pressure.

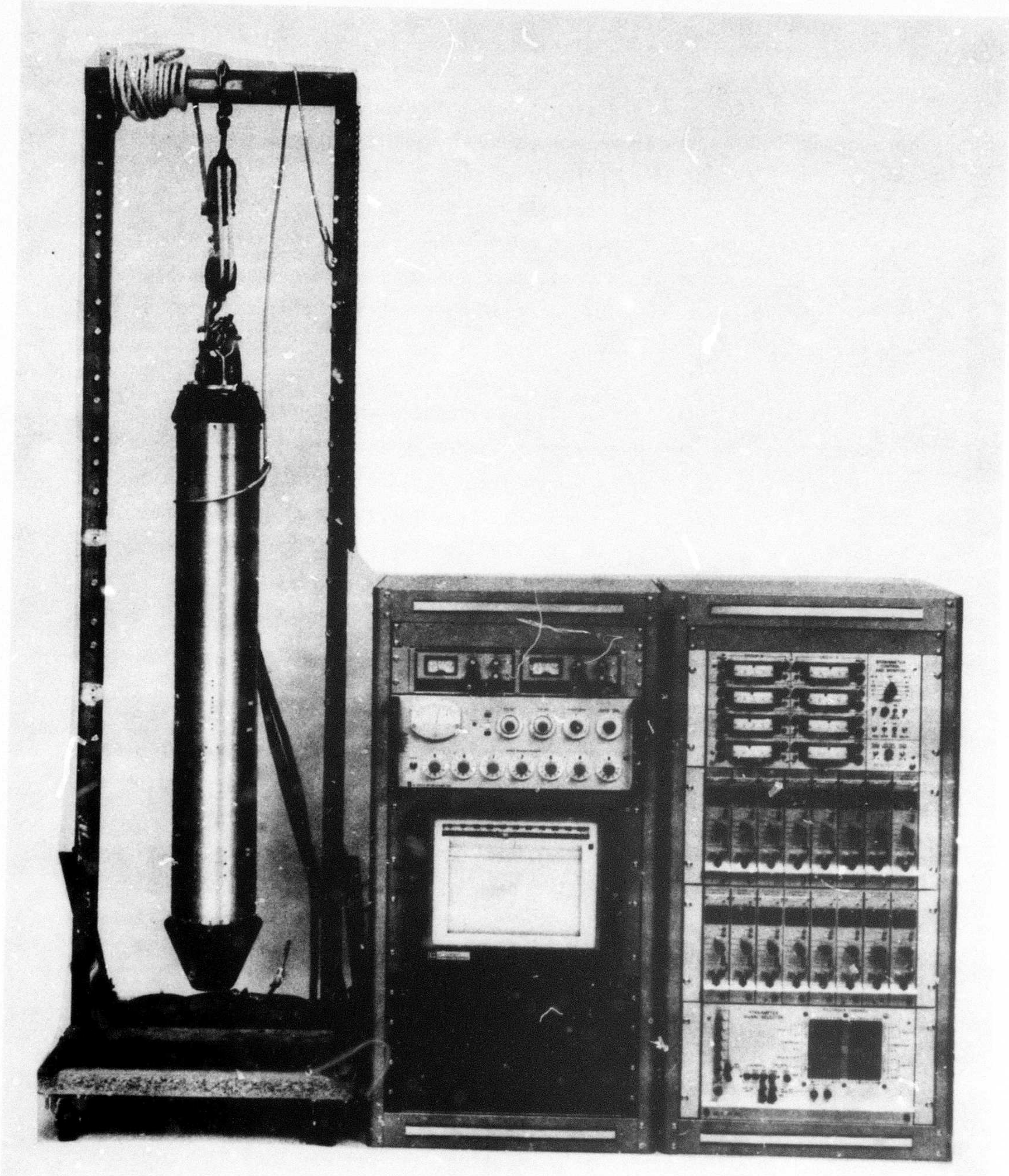


FIGURE 1

SHALLOW HOLE STRAINMETER SYSTEM

2. STRAINMETER DESIGN

The short baseline strainmeter developed will make highly sensitive earth strain measurements in boreholes on the order of 8 inches in diameter. Since the ultimate applicability of the borehole strainmeter is at depths of several thousands of feet, this objective was emphasized in the design. However, the first strainmeter produced on this program was installed in a shallow mine tunnel location and so did not include some of the features that would be required for deeper installations.

The instrumentation for performing borehole strain measurements consists of two subsystems; the downhole instrument canister and the wellhead subsystem. The general system design goal characteristics are summarized in Table 1.

The downhole instrument canister, or strainmeter, contains strain sensors and high reliability electronics to amplify, detect, and transmit the strain data. The downhole instrument is connected to the surface by a multiconductor cable. The design permits it to be positioned at the required depth, solidly coupled to the walls of the borehole by grouting and operated over extended time periods.

The wellhead subsystem consists of standard electronics to process and record the acquired data. Auxiliary equipment to power, monitor, calibrate and control the downhole equipment is also included.

TABLE 1

NOMINAL STRAINMETER CHARACTERISTICS

RANGE*	High Gain: $\pm 10^{-6}$
	Low Gain: $\pm 10^{-5}$
RESOLUTION	High Gain: 10^{-9}
	Low Gain: 10^{-8}
STABILITY	Short Term: $<10^{-9}$/day (max)
	Long Term: $\pm 3 \times 10^{-7}$/year (max)
NOISE LEVEL	$<10^{-9}$rms max strain in 1-Hz bandwidth
SYSTEM TEMPERATURE COEFFICIENT	$\pm 2 \times 10^{-6}$/°C (max)
SYSTEM BANDWIDTH	
Strainmeter	dc to 100 Hz
Wellhead(selectable)	dc-0.05 Hz, dc-10 Hz, dc-100 Hz
SENSOR ZERO SET	Less than $\pm 5 \times 10^{-8}$
SENSOR ORIENTATION	
Horizontal Strain	Up to six sensors spaced at 60°
Vertical Strain	Two sensors mounted opposite each other
TEMPERATURE MEASUREMENT	
Range	<0°C to >130°C
Relative Accuracy	±0.001°C
Absolute Accuracy	< ±0.1°C
Stability	< ±0.005°C/month

*Compressive strain has been defined as positive. Range is nominal and actual value depends upon individual sensor calibration.

2.1 INSTRUMENT CONCEPT

A multicomponent strain sensor assembly was selected instead of a simpler volumetric strainmeter assembly because of the desire to obtain more information about the nature of the strain field. With 3 horizontal sensors oriented arbitrarily the latitudinal, $e_{\phi\phi}$, meridional, $e_{\lambda\lambda}$, and shear components of strain, $e_{\phi\lambda}$, can be resolved. Furthermore, with a vertical component strainmeter, one obtains further information on the strain components e_{rr}, $e_{r\lambda}$ and $e_{r\phi}$. The borehole strainmeter design selected allowed for four horizontal component sensors and two vertical sensors to provide important measurement redundancy of earth strains and verification of performance.*

A volumetric strainmeter only responds to the dilatational component of strain $\Delta = e_{rr} + e_{\phi\phi} + e_{\lambda\lambda}$ and it is impossible to separate the strain components. With a multicomponent strainmeter, it is a simple matter to compute the dilatational component of strain if desired.

The response of a near-surface vertical strainmeter can ideally be related to the horizontal strain components with the simplifying assumption that $\lambda=\mu$.

$$e_{rr} = -\frac{1}{3}(e_{\phi\phi} + e_{\lambda\lambda})$$

Observe that the shear strain $e_{\phi\lambda}$ is not present in the expression for vertical strain and e_{rr} is proportional to the areal strain $(e_{\phi\phi} + e_{\lambda\lambda})$ It was our intent with a borehole installation to examine the magnitude of the vertical component of strain and examine whether topographic irregularities, atmospheric loading, etc., on this component cause a disturbing perturbation from the above estimate, based on a flat plane layered halfspace.

* For a discussion of the general theory of earth tides see "Areal Strain of Solid Earth Tides Observed in Ogdensburg, N.J.", by John T. Kuo, J. Geophys. Research, Vol 74, No. 6, pp 1635-1644, 1969.

Another reason for selecting a multicomponent strainmeter package was the desire to be able to record seismic strains from nuclear explosions and distant earthquakes. When a strainmeter is used as a detector of seismic waves, its amplitude and phase response depends on the aximuth of approach of the seismic wave, its wave period, its apparent velocity and the type of wave particle motion involved - longitudinal or transverse. It would be impossible to determine the azimuth of approach or the type of seismic wave involved if only a volumetric strainmeter were used, e.g., as in determining the nature of the strain release associated with an underground explosion.

2.2 STRAINMETER MECHANICAL DESIGN

The downhole instrument consists of a thin-wall stainless-steel canister containing strain sensors which is connected to the surface by a multiconductor armored cable in deep installations, and coupled to the rock by an expansive cement. A portion of the canister may be pressure sealed by the use of modules to protect the electronics while the remainder is fluid filled and in hydrostatic equilibrium with the borehole fluids. In addition to the strain sensors and associated electronics, the instrument canister also contains devices for remotely calibrating and zeroing the sensors, measuring temperature, equalizing pressure and aiding installation. Key mechanical design considerations were as follows:

- Withstand the rigors of emplacement
- Exhibit a high degree of mechanical stability
- Detect very small mechanical displacements
- Reset precisely to zero and provide mechanical calibration

The basic design concept was directed toward solving the crucial problem of coupling the strain measuring elements to the rock and producing a minimum perturbation due to the instrument case, grout, etc., over long periods of time.

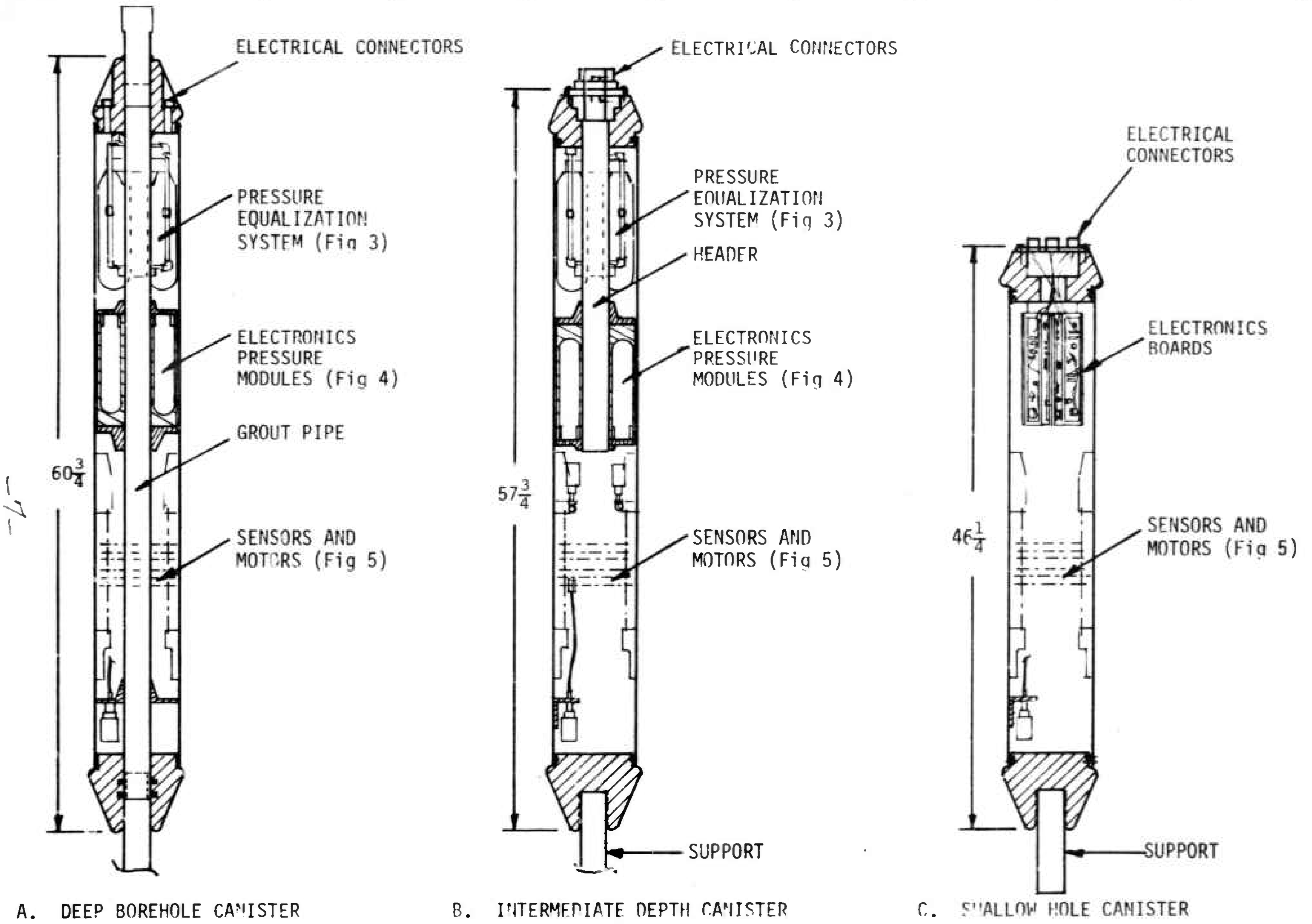
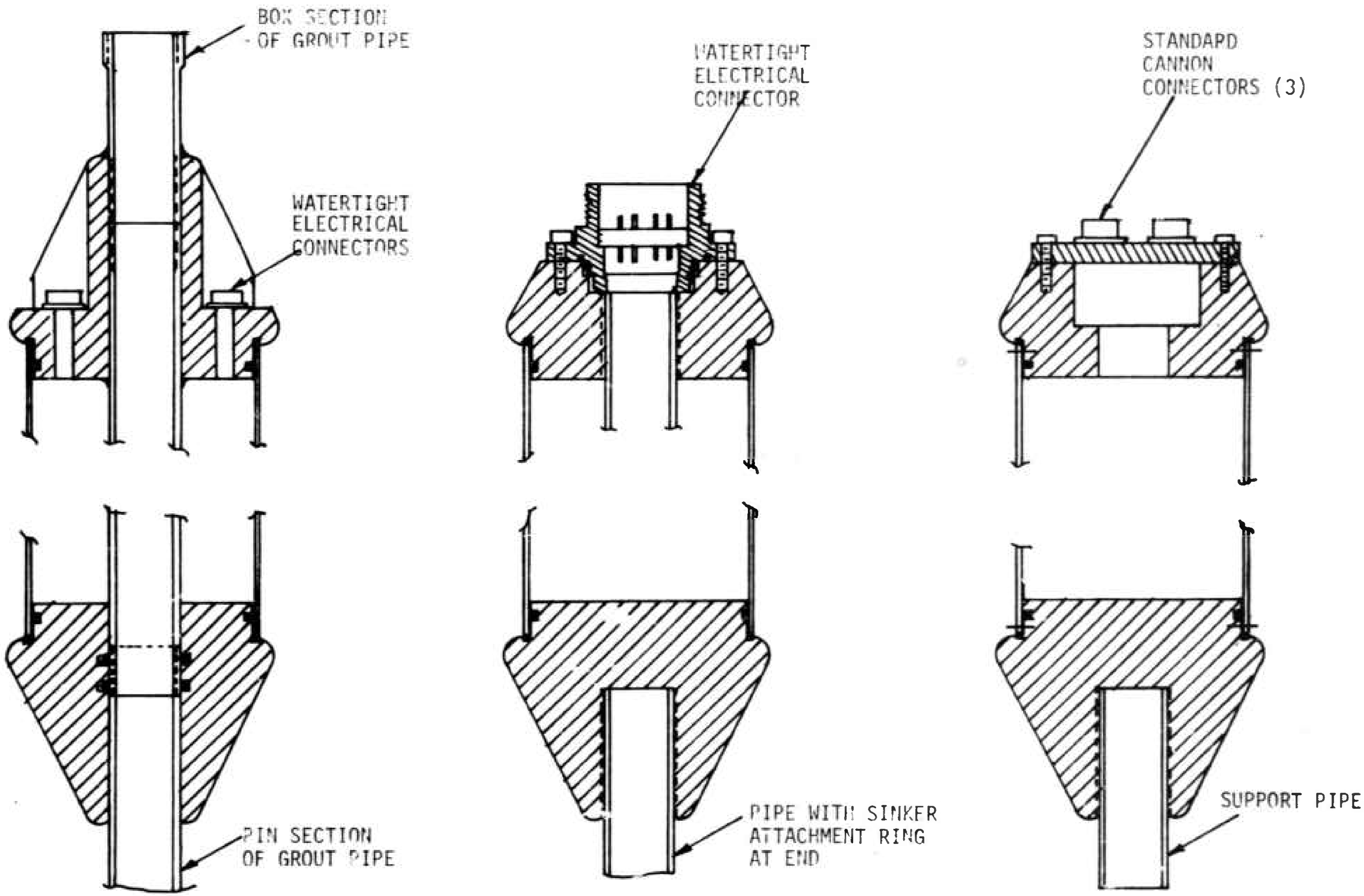


FIGURE 2
STRAINMETER CANISTER DESIGNS

2.2.1 Strainmeter Canister Design

The downhole strainmeter instrument package consists of a thin-wall fluid-filled cylindrical stainless steel canister to which the strain sensor are mounted. The roughened surface of the 6-1/2 inch diameter tube is coupled to the borehole walls with an expansive grout. Thus, relative strain in the surrounding rock causes the ister walls to be deformed in direct proportion and this deformation is detected by the sensors. Since the effective modulus of the 1/8" thick wall canister is small compared to that of the surrounding rock, it is relatively compliant and it is possible to take advantage of the amplification of transverse strain which occurs at the surface of an empty hole. Three configurations have been considered depending on whether the application is for very deep, intermediate, or shallow holes. Figure 2 illustrates the three basic designs. The differences are principally determined by the method of grouting used and whether the application is submerged. The basic canister length ranges from 4 to 5 feet and weighs from 180 to 300 pounds depending on the case being considered.

Heavy end caps provide rigidity and protection during installation (see Figure 3). They are tapered to prevent hangups in the borehole and include tapered fins around the periphery which extend beyond the nominal canister diameter to ensure that the grout gap is a minimum of one half inch. The top end cap must also accommodate the electrical connectors, pressure equalizer tubes, fill ports and any mechanical support attachments. For very deep installations it is necessary to pump the grout through the instrument canister by means of a central section of grout pipe (which is also used to support the electronics modules, motors, etc) as illustrated in Figure 2A. The end caps are mechanically attached to this section of grout pipe which is the load bearing member of the structure. The thin canister side wall is mechanically isolated from the end caps in this configuration and sealed by O-rings which protects the sensors from loads and shock. Short pin and box sections of regular grout pipe are permanently attached to each end cap and the bottom end cap is threaded onto the upper section of grout pipe.



A. DEEP BOREHOLE CASE B. INTERMEDIATE DEPTH CASE C. SHALLOW HOLE CASE

FIGURE 3
END CAP DETAILS

For intermediate depth applications, where it is possible to bail grout into the borehole and subsequently sink the instrument canister into the grout, it is possible to considerably simplify sensor mounting and final assembly by deleting the pipe through the center of the assembly, as illustrated in Figure 2B. The thin-wall canister shell is rigidly attached to the end caps which eliminates some shock protection; but the use of a flexible cable and sinker weight arrangement is a suitable tradeoff. Mechanical support of the instrument canister is provided by a single connector and armored load-bearing cable arrangement. The electronics pressure modules are supported from the top end cap by a short section of pipe.

For shallow hole installations, where standing water is not a problem, the canister is simplified even further as illustrated in Figure 2D, by deleting the pressure equalizer arrangement to shorten the canister and using standard environmentally resistant electrical connectors.

The canister is prevented from collapsing at high pressure by a system which equalizes the pressure of the borehole fluid and the instrument fluid, which is an inert fluorocarbon compound designated Fluorinert FC-43 and produced by the 3M Company. The fluid is characterized by good dielectric, thermal, and handling characteristics. Additionally, it is chemically stable, immune to contaminating effects, and does not leave a residue after evaporating.However, the relatively high temperature coefficient of expansion could result in a fluid volume change of approximately 15% from a 100°C temperature change such as could be encountered in very deep installations. Thus the pressure equalizing system must also compensate for fluid volume changes due to temperature, compression and grout expansion. The system also provides for a possible requirement to attenuate high frequency barometric pressure effects. Alternative solutions, such as bellows, or relief valve arrangements were generally inadequate due to the need to compensate for fairly large volume changes and bidirectional flow during emplacement.

The approach chosen, illustrated in Figure 4, consists of bladders which can be fabricated from silicone rubber to operate in temperatures greatly in excess of 85°C to isolate the borehole and instrument fluids. A net-

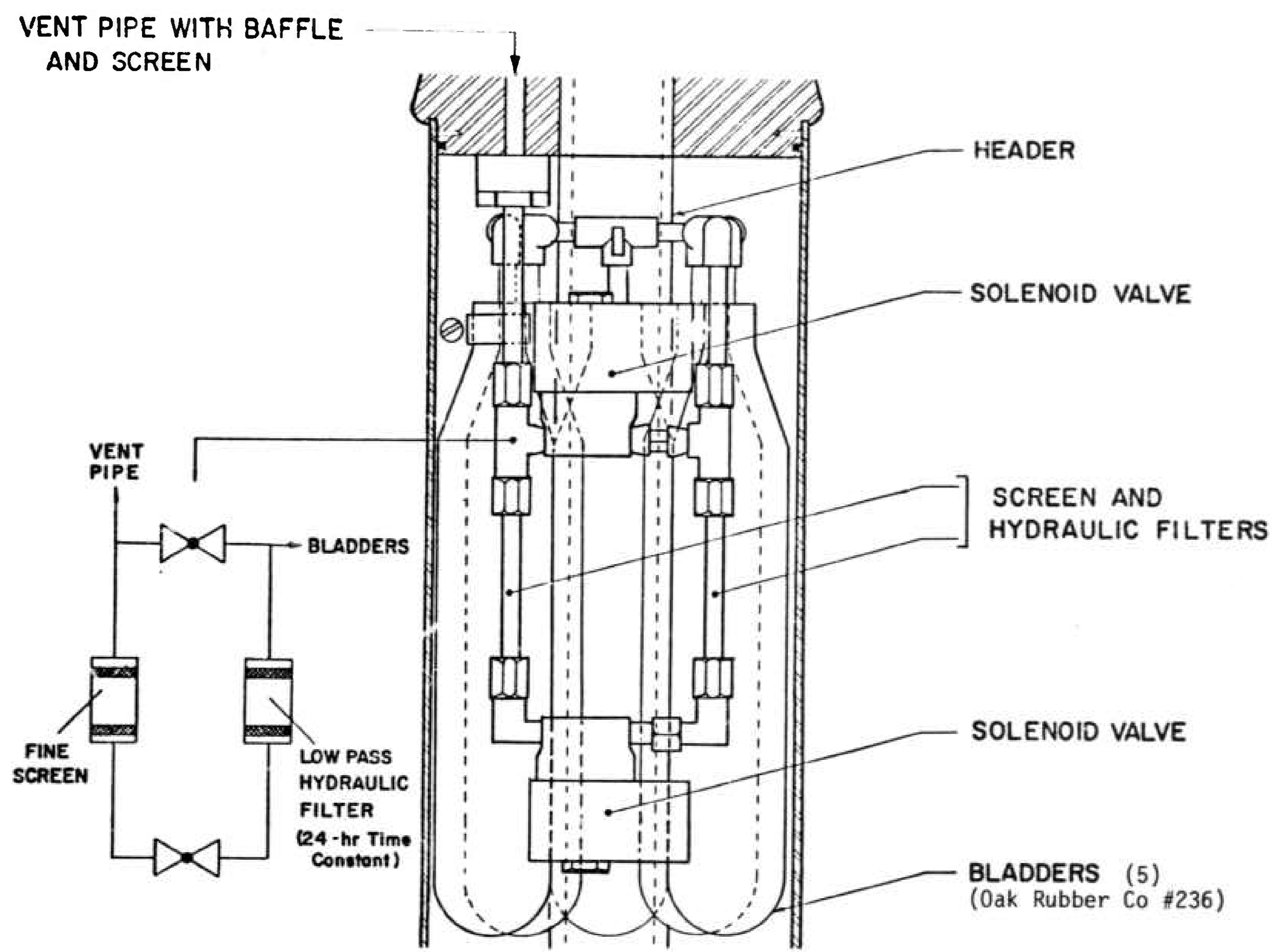


FIGURE 4

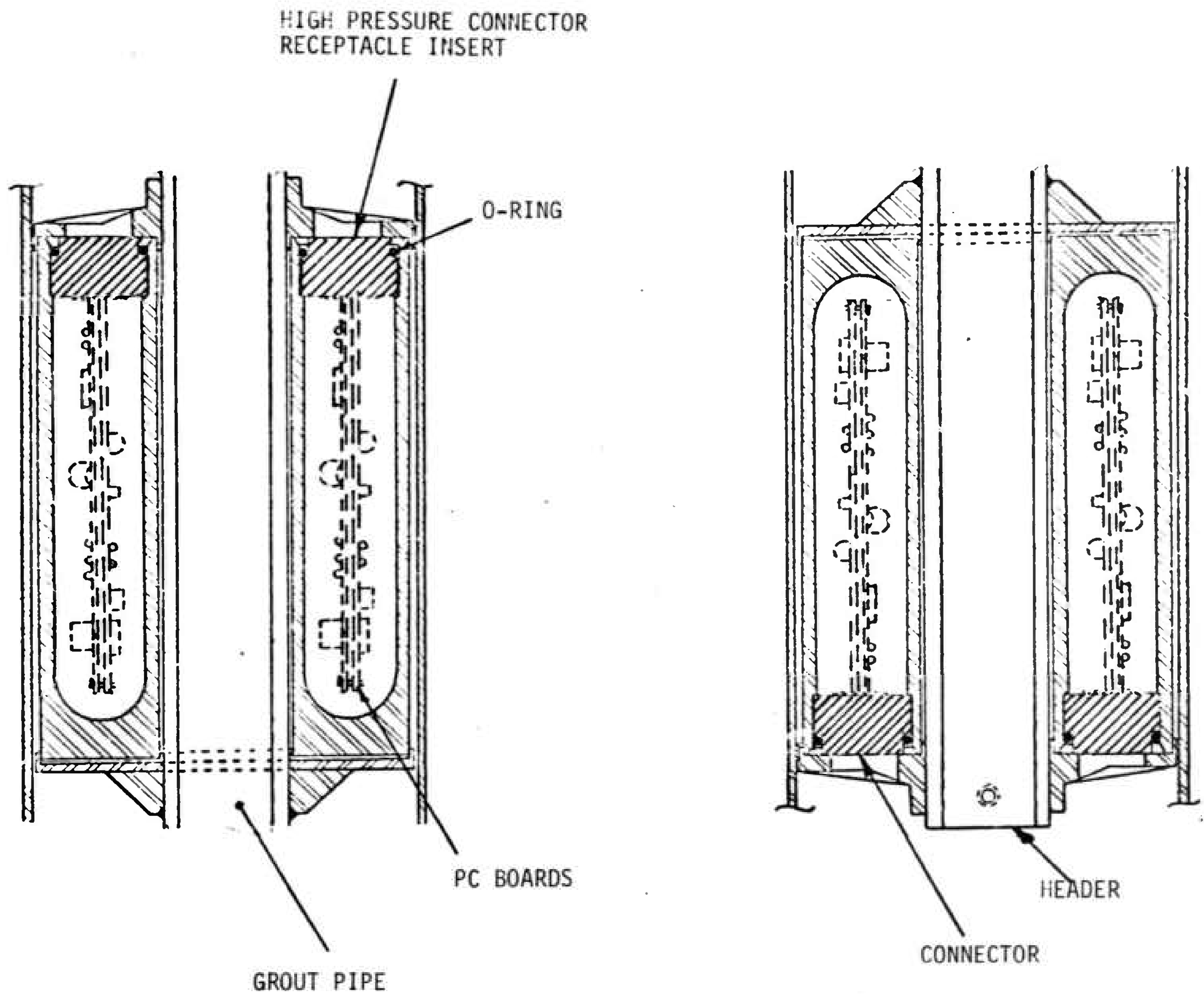
PRESSURE EQUALIZATION SYSTEM

(Deep Hole and Intermediate Hole Canisters)

work of solenoid valves is used to shut the system off or cut in a 24-hour hydraulic low pass filter for attenuating atmospheric pressure variation effects. A 1/4" standpipe, which is adequate for the maximum flow rates expected, is used to connect the bladders to the borehole fluid at a point above the maximum level of the first grout stage. A baffle is used to protect the pipe from particulate matter. The approach is fail safe in the sense that instrument fluid is heavier than water; thus preventing damage to critical components in the event a leak does occur.

For applications involving hydrostatic pressure, the downhole electronics are contained in 6 small-diameter pressure vessels located within the thin-wall canister (see Figure 5). The approach of using separate modules was chosen because of the small annular volume available which made it necessary to minimize the pressure vessel wall thickness. Electrical connection into the modules is made through a modified high pressure connector insert which is O-ring sealed and held captive by the assembly support structure. The interconnecting harness and standard cable plugs are directly exposed to the inert instrument fluid and no special precautions are needed to protect them. The modules are hollow steel cylinders approximately 2 inches in diameter and 9 inches long which are fabricated from T1-F high strength steel manufactured by US Steel. These modules are rated and have been tested at pressures up to 5000 psi, adequate for a 10,000-foot borehole. The electronic printed circuit boards are attached directly to the instrument fluid to aid thermal dissipation and inhibit corrosion effects.

Although only one vertical sensor and three horizontal sensors are necessary to meet the minimum measurement objectives, provisions have been made to incorporate up to twice that amount in the canister, if necessary. Operational redundancy is desirable to maximize the probability of obtaining meaningful data from an expensive and permanently emplaced instrument in spite of the possible failure of a single channel during emplacement or operation over an extended lifetime. Measurement



A. DEEP BOREHOLE CASE

B. INTERMEDIATE DEPTH CASE

FIGURE 5

ELECTRONIC PRESSURE VESSEL MODULES AND MOUNTING

redundance is desirable to evaluate anomalous behavior that may be due to individual sensors, localized grout bond failures, or fractured borehole conditions. While a wide spacing between sensors will ultimately be preferred to avoid undesirable local conditions, a compact grouping is preferred initially to aid the comparison of sensor performance and instrument evaluation.

The sensors are spaced and mounted as illustrated in Figure 6. Complete redundancy would rarely be required and the shallow hole version installed on this program contained both vertical sensors but only one extra horizontal sensor, H3B, to provide the desired measurement redundancy. Additional sensors were unnecessary since the physical risk was small and there was a need to limit instrument size. The sensor end supports are mounted directly to the canister by the use of screws through the outside of the canister wall. Sealing is accomplished by the use of compressed O-rings around the screws on the inside since only low differential pressures are encountered. This same technique is used to mount the brackets for the sensor positioning motors, flexible drive shaft guides, temperature probes and any other hardware that cannot be supported from the end caps or grout pipe.

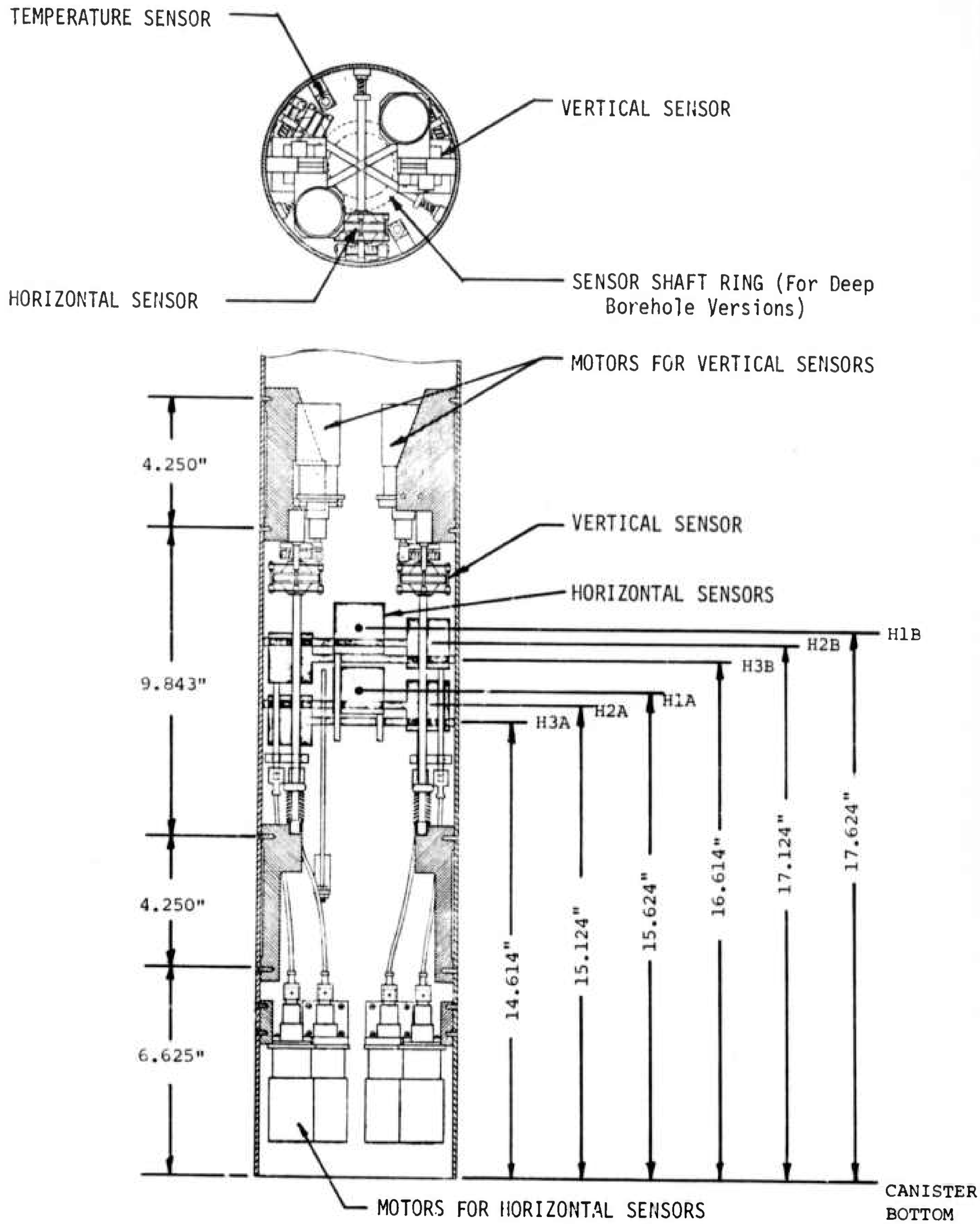


FIGURE 6

SENSOR AND MOTOR MOUNTING AND SPACING

.1125-1

2.2.2 Strain Sensor Design

The strain sensor, Figure 7, is a short baseline quartz rod extensometer with capacitance plate sensing elements. The sensors are anchored to diametrically opposite points of the thin-wall stainless steel cylinder in the horizontal sensor case and axially along the walls in the vertical sensor case. The effective baseline length of the horizontal sensors (Figures 8 and 9) is approximately that of the canister diameter, 6-1/2 inches (165 mm). Since the vertical sensors (Figure 7) are not affected by the magnification of strain transverse to the hole, their effective base length of approximately 10 inches (254 mm) was made longer to provide output levels more nearly equivalent to that of the horizontal sensors. The capacitance plates are wired as a fully balanced bridge circuit which is driven by a stable reference signal (Figure 8). When the walls of the cylinder move due to strain changes coupled from the surrounding rock, a low level output signal is produced by the resulting bridge imbalance which is directly proportional to the sensor deflection.

The principal design constraints, aside from those of size, were imposed by the need to avoid damage due to deformation during emplacement and achieve a high degree of mechanical stability in operation. A gross deformation allowance of 0.050 inch (1.27 mm) has nominally been used in the sensor design for transient, i.e., elastic, deformations. It is believed that the real permanent deflection limit is more like 0.005 to 0.010 inch (0.13 to 0.25 mm); that is, essentially no deformation can be allowed since larger deformations would keep the sensors from functioning properly, if it did not in fact destroy them. Possible sources of deformation are denting during installation due to rock falls or stresses due to binding of the canister or drill train in the borehole. These conditions should not be a problem if a cased borehole which meets minimum curvature requirements is used, effective use is made of borehole instrument centralizers and the canister length is held to a minimum. The use of a dummy package or mandrel just prior to actual instrument installation will be a valuable means of determining the probable

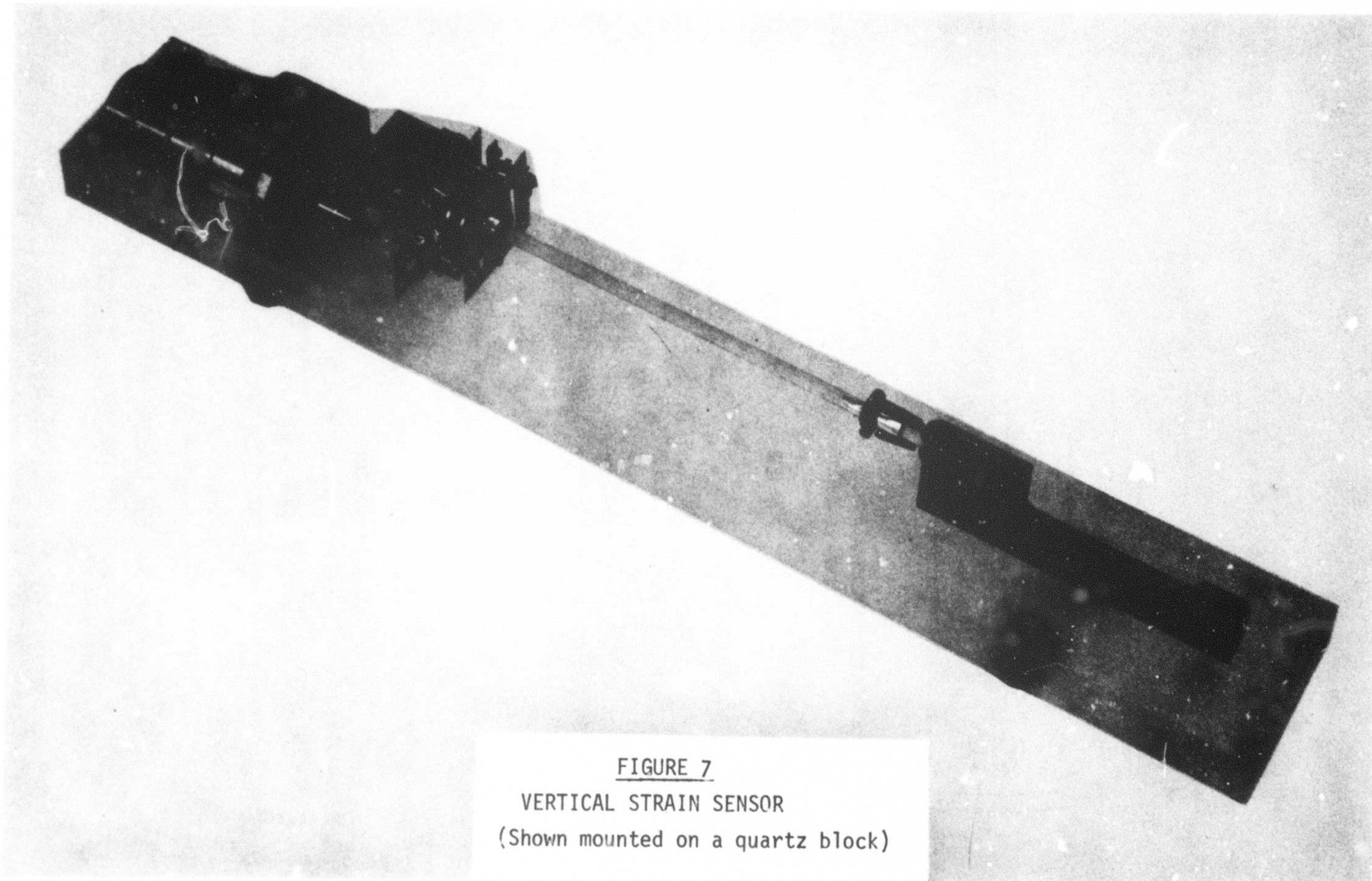
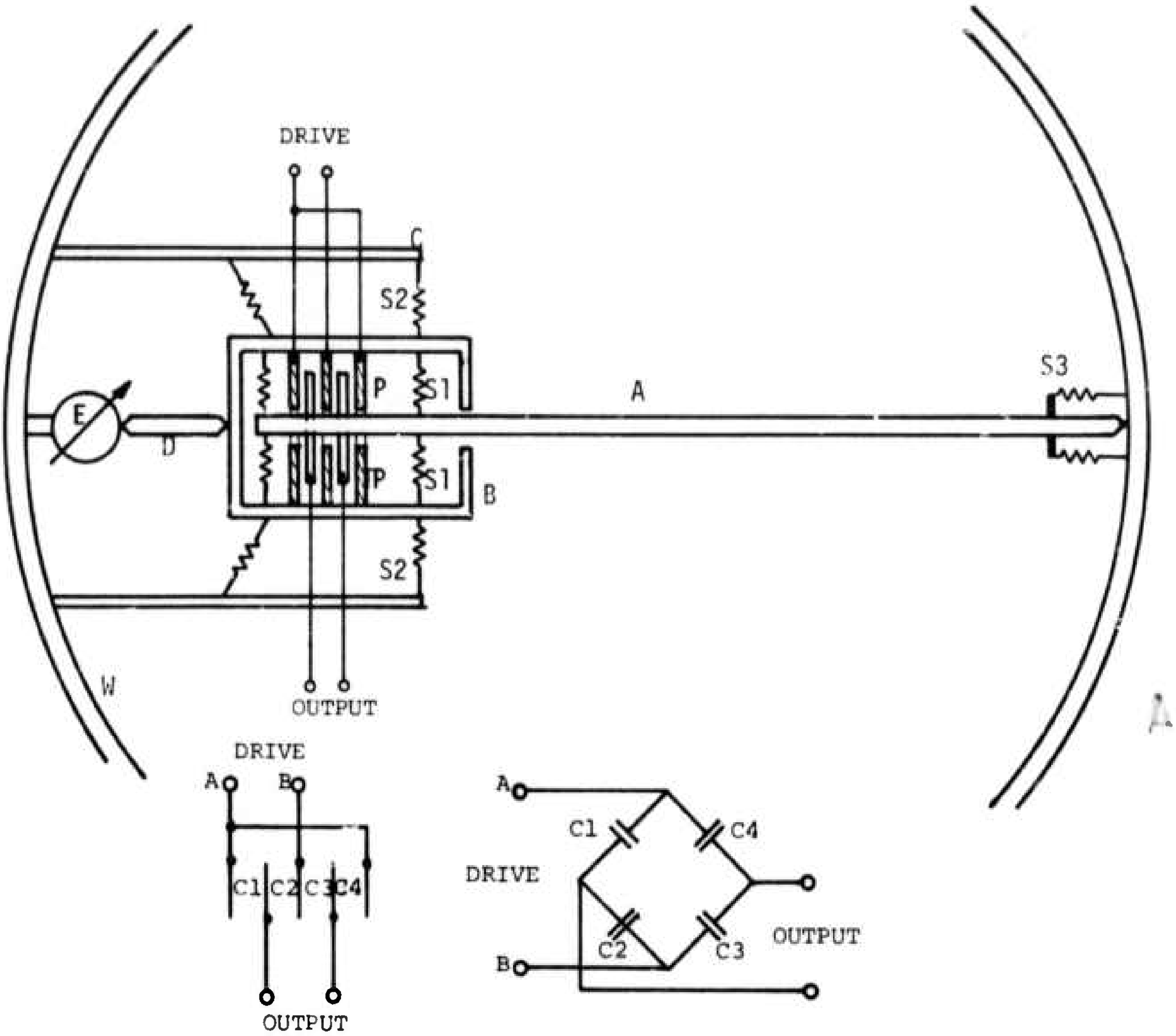


FIGURE 7

VERTICAL STRAIN SENSOR

(Shown mounted on a quartz block)



A	QUARTZ SHAFT
B	CAPACITOR HOUSING
C	SUPPORT
D	INTERPOSER SHAFT
E	ZERO & CALIBRATE MECHANISM (Motor, Gears, & Lead Screw)
P	CAPACITIVE PLATES
S1	DIAPHRAGMATIC SPRINGS
S2	INVERTED CANTILEVER SPRINGS
S3	END LOADING SPRINGS
W	CANISTER WALL

FIGURE 8

STRAIN SENSOR MECHANICAL SCHEMATIC

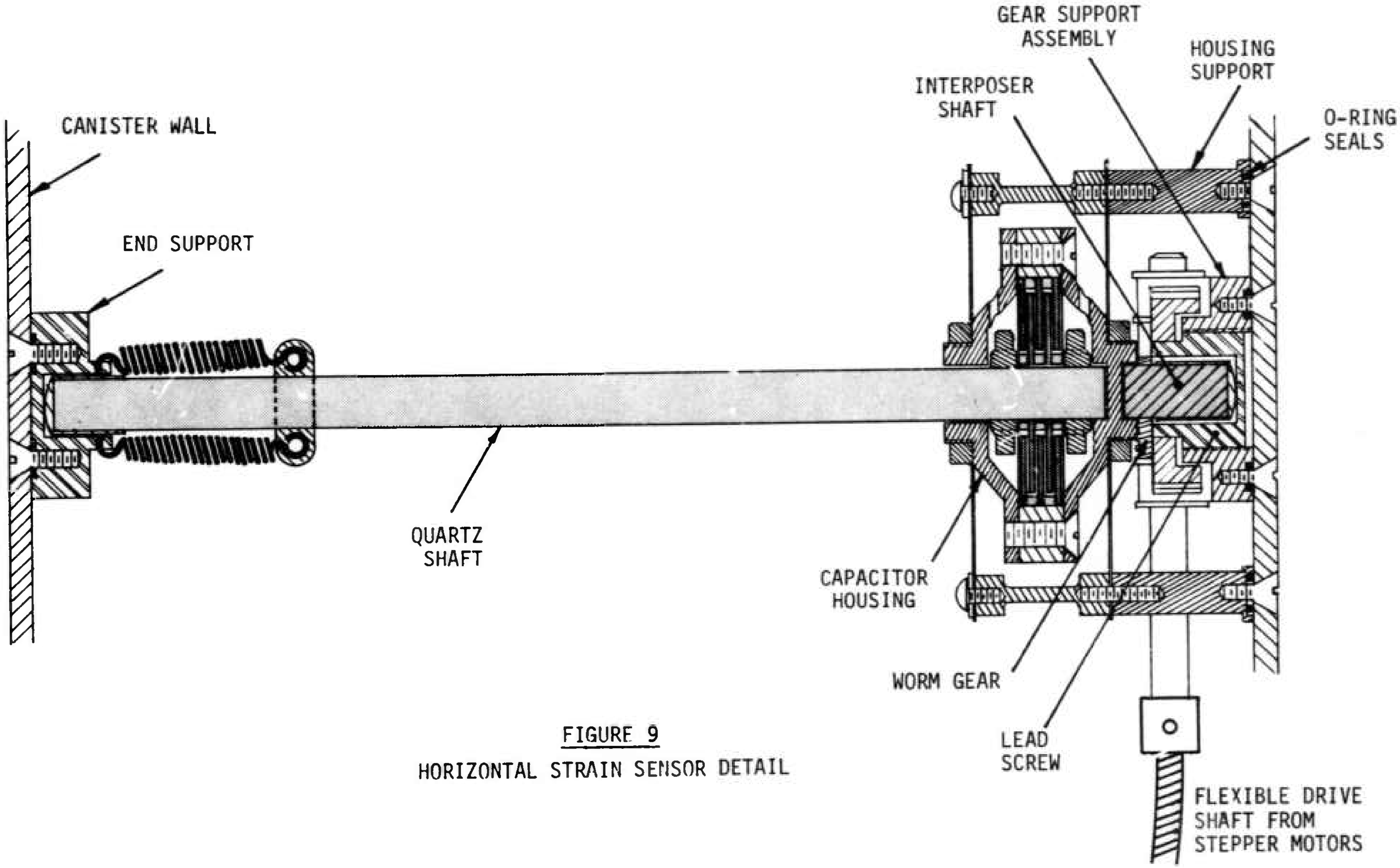


FIGURE 9

HORIZONTAL STRAIN SENSOR DETAIL

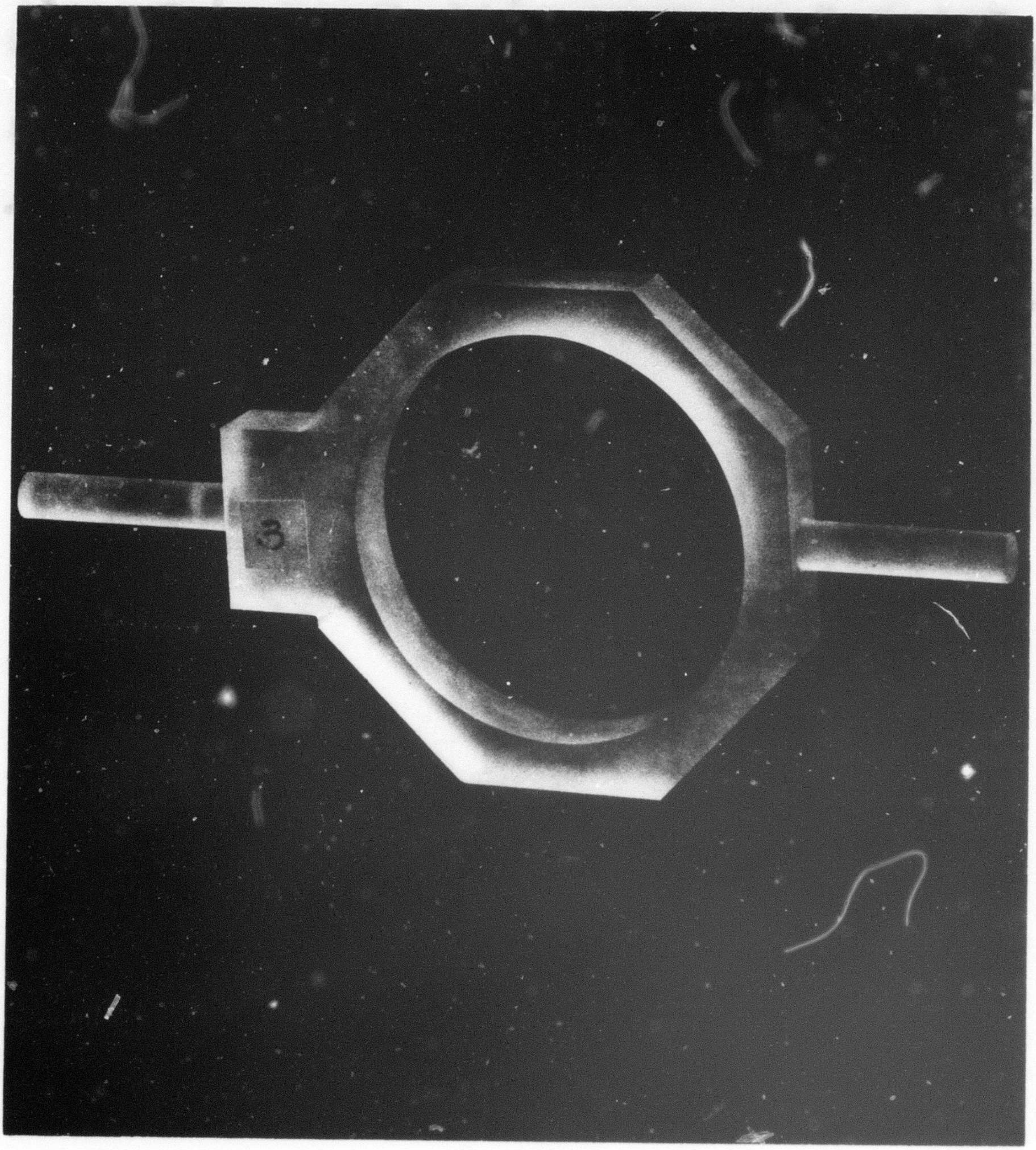


FIGURE 10

ANNULAR RING SHAFT

success of the installation. The requirements for protection and risk increase significantly in an uncased hole. It was not possible to define quantitative shock and vibration levels that will be encountered during installation. The tentative conclusion is that reliance will have to be placed on the instrument train mass and slow careful installation techniques to keep the shock level down. A design goal of 0.1 g was used for the shock level that might be expected during operation resulting from a magnitude 4 earthquake event located 2 kilometers away.

The sensors consist of 0.250 inch diameter (6.35 mm) quartz rods with a quartz and stainless steel capacitor housing fastened on one end and mechanisms for supporting and positioning the sensor assembly as illustrated schematically in Figure 9. It was determined that annealed fused quartz and 303 stainless steel materials are sufficiently stable and the use of more exotic low-coefficient-of-expansion materials was not necessary. The main quartz shafts are 5.437 inches (138 mm) and 8.593 inches (218 mm) long for the horizontal and vertical sensors, respectively. For those applications which require a grout pipe through the center of the instrument canister, an annular ring version of the horizontal shaft can be machined from quartz as illustrated in Figure 10.

The details of the capacitor housing assembly are illustrated in Figure 11. Two capacitor plates and three quartz spacers are held on the shaft by using nuts which compress around the shaft. A rigid assembly is made by placing the unit under a heavy load along the shaft before tightening the compression nuts. Three capacitor plates are held within the housing by compressing the plates and two spacers between stainless steel outer plates. The spacers used are 0.012 inch (0.305 mm) thicker than the plates. All of the plates and spacers are lapped in groups so, when they are assembled, a precise 0.006 inch (0.152 mm) spacing is maintained between each adjacent plate. The compression nuts are placed so that they are nominally 0.004 inch (0.101 mm) from the capacitor housing and thus serve to limit sensor travel before adjacent capacitor plates can contact.

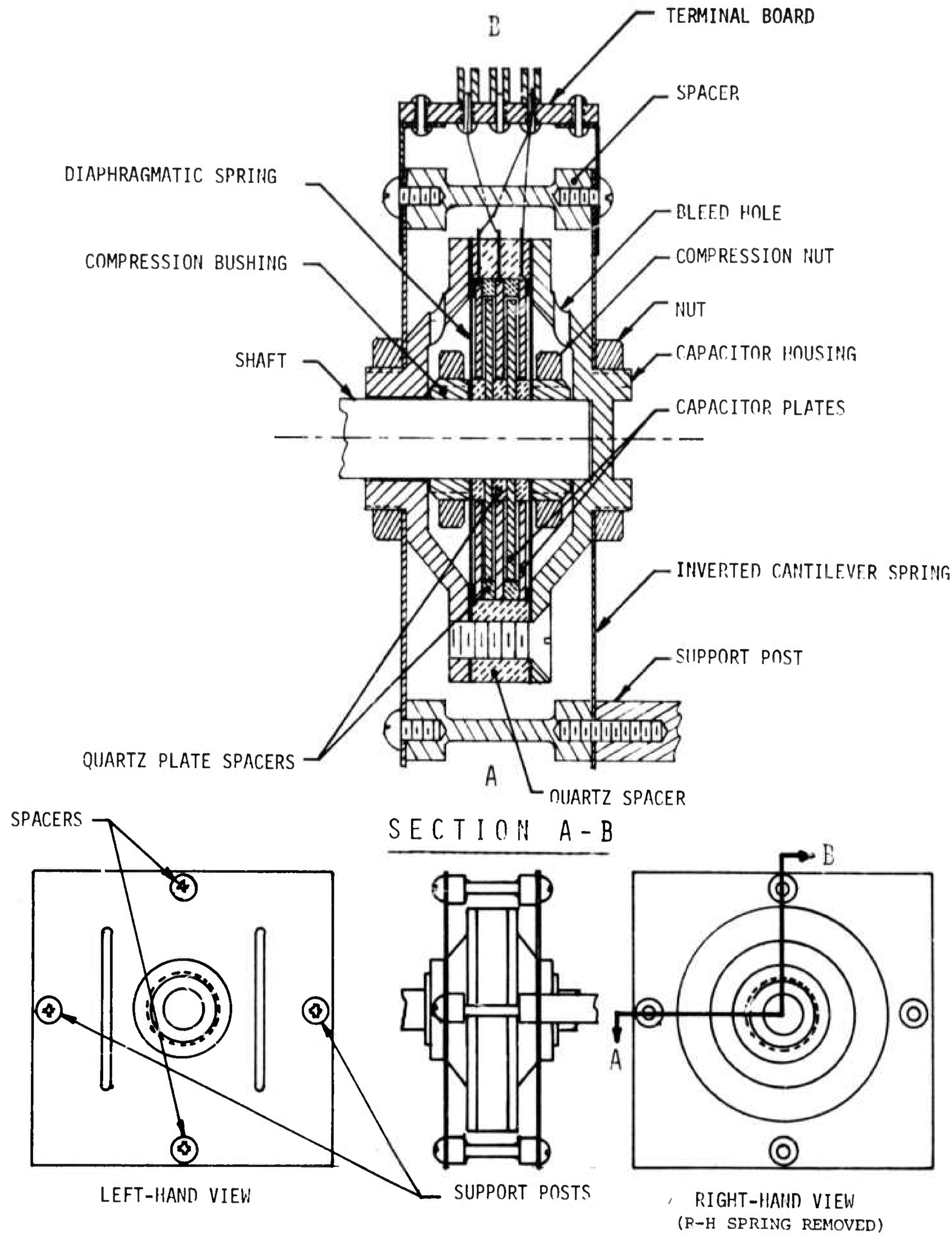


FIGURE 11

STRAIN SENSOR DETAIL

The compression nuts consist of a threaded split bushing with a tapered end and a threaded compression nut tapered to fit the bushing. When the nut is tightened, the tapered surfaces and the slit in the bushing cause the inside diameter of the bushing to reduce until a firm mechanical joint is produced. A thin layer of aluminum foil is used between the bushing and the quartz shaft to produce a uniform stress.

Ideally, the inner shaft and its plates are not coupled to the housing. practically, however, a cantilevered shaft is not possible. Therefore, two diaphragm springs are used to support the shaft assembly from the housing. The diaphragm spring is very weak in the axial direction and does not inhibit relative motion of the shaft and housing. Thin mylar shims are used to insulate the diaphragm spring from the capacitor plates and take up tolerances.

The capacitor housing is connected to two inverted cantilever springs which are fastened to the canister walls by two standoff supports. The inverted cantilevel springs isolate the capacitor housing from canister wall distortions and are prestressed to provide several pounds of loading on the lead screw that is used to position the sensor. The loading is principally provided by the outboard spring to avoid distorting the housing and the change in loading over the operating range is so small that it does not affect normal sensor operation. Thus, the housing is supported by the combination of springs and standoffs but it is free to move axially to the limit of stops provided by the compression nuts in the capacitor assembly.

The free end of the quartz shaft is anchored to the canister wall using spring pressure to provide several pounds of loading as illustrated in Figure 9. This is accomplished by fastening the springs to a shaft compression grip and then fastening the springs to a wall clamp which permits the shaft to seek its own alignment with the canister wall. Such an arrangement is necessary to prevent shaft breakage during assembly or due to canister deformation.

Interposed between the canister wall, or end support in the case of the vertical sensors, and the capacitor housing is a worm-gear-driven precision lead screw, illustrated in Figures 8 and 9. The worm is driven by a stepper motor and planetary gear reduction assembly to produce lead screw motion in a direction parallel to the capacitor housing axis. In the case of the vertical sensors, the motor assembly is mounted right on the sensor assembly and the worm is driven through a beveled gear (see Figure 7). The motor assemblies for the horizontal sensors are located near the bottom of the canister and drive the sensor worms through flexible shafts.

The motion produced in response to each step of the motor is summarized in Table 2. The values were chosen to permit precise setting and calibration even on the most sensitive scales. When the lead screw is threaded all the way into the gear support assembly, there is a distance of 0.050 inch (12.7 mm) between the lead screw and the interposer shaft to provide protection for the quartz pieces should any deformation of the canister take place during emplacement.

TABLE 2

SENSOR ZERO MECHANISM DRIVE CONSTANTS

	PROTOTYPE	FINAL DESIGN
Stepper Motor	1/4 Turn/Step	1/4 Turn/Step
Motor Gear Head Reduction	130.479:1	685.157:1
Worm Gear Reduction	48:1	50:1
Lead Screw	50 Turns/Inch	52 Turns/Inch
Sensor Displacement	7.983×10^{-7} Inch/Step	1.403×10^{-7} Inch/Step

To operate the sensor, the lead screw is advanced until it contacts the interposer shaft which then drives the sensor capacitor housing until the capacitor plates are centered and a null is produced in the capacitance bridge network. The plates on the shaft cannot move since the shaft is held hard against the opposite point of the canister wall.

The gear support assembly is split to permit as much backlash to be removed from each sensor as is practical by tightening a set screw. This, in conjunction with the loading on the lead screw provided by the inverted cantilever spring, produces a relatively uniform and reproducible motion. It is also quite stable when at rest for normal sensor operation as well as being relatively shock resistant, and no deleterious effects have been observed. In addition, it has never proven necessary to decouple the rest of the gear train from the worm gear to avoid spurious motion. Although there are some minor variations in the motions produced from step to step, the average results are quite reproducible and no significant variations have ever been observed due to variations in thread pitch. The only irregular behavior observed with this arrangement is when the direction of motion is reversed there is a brief period of erratic motion but the situation quickly restabilizes and the turnaround effects can be discounted. Thus, this mechanism is entirely adequate for average calibration purposes.

The zeroing mechanism drive motor is an American Electronics, Inc. Model 15TA9 stepper motor. It is a 90° step, two-phase, three-wire design that, with gear reduction, provides the required resolution and allows the downhole cable leads to be minimized. Motor operation results in less than 4 watts of dissipation and is designed to be operated in insulating fluids at 5000 psi. Although the temperature rise produced by the motor dissipation does affect the sensor output after a period of time, it is relatively easy to avoid calibration errors by performing the operation quickly or by averaging the results from a bidirectional test.

2.2.3 Strain Sensor High-Pressure Development Tests

Testing was performed to evaluate the strain sensor and zero mechanism operation at hydrostatic pressures up to 5000 psi, the system-designed maximum. Principal parameters evaluated were scale factor variations, mechanical pressure coefficients, and stability. The testing was conducted using the final configuration of the laboratory model strain sensor mounted in a quartz test fixture. The laboratory model sensor differs only slightly from the final sensor design and the results are considered representative of the final design. However, the direct test results are for the net behavior of the sensor and the test fixture and must be evaluated in terms of the actual strainmeter configuration. Refer to Figure 12 for a photo of the laboratory model strain sensor and the following page for the test results on that sensor. The pressure coefficient of the sensor and test fixture was determined to be on the order of $+5 \times 10^{-9}$/psi for large pressure excursions. There was an approximately 2-to-1 uncertainty in the experimental results due to some apparent hysteresis effects and a conservative value of $+10^{-8}$/psi should be used for worst case analysis. These values are roughly consistent with the value expected to result from the approximate 10% unbalance that exists due to the relative proportion of quartz and stainless steel. Thus, the effective sensor modulus can be considered to be greater than 10^8 psi, which is considerably higher than the average rock modulus that can be expected to range from 5 to 20 x 10^6 psi. Therefore, the sensor pressure coefficient will be insignificant compared to rock under actual operating conditions. Additional accuracy in determining the pressure coefficient of the sensor was not considered necessary.

The effect of pressure on sensor linearity and scale factor were determined by operating the stepper motor-driven zero mechanism over a known distance to produce a full span electrical output. As would be expected, pressure had no significant effect on linearity. There was a nonlinear 5% decrease in sensor scale factor sensitivity as the pressure was increased to 5000 psi. However, it is possible that air bubbles were trapped in the sensor and not adequately removed prior to starting the calibration sequence. A later check resulted in a much less significant change. This test also demonstrated the ability of the zero mechanism

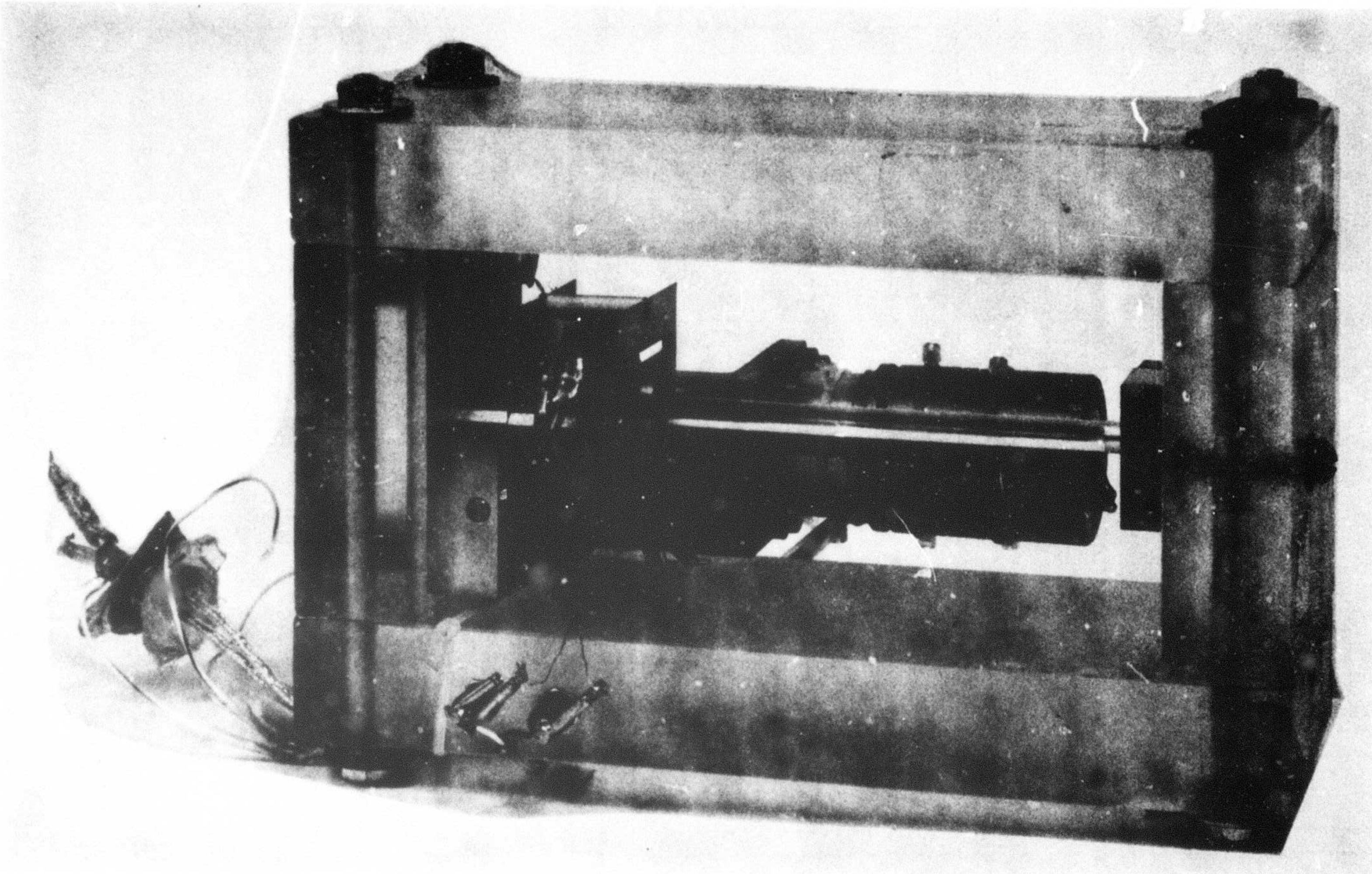
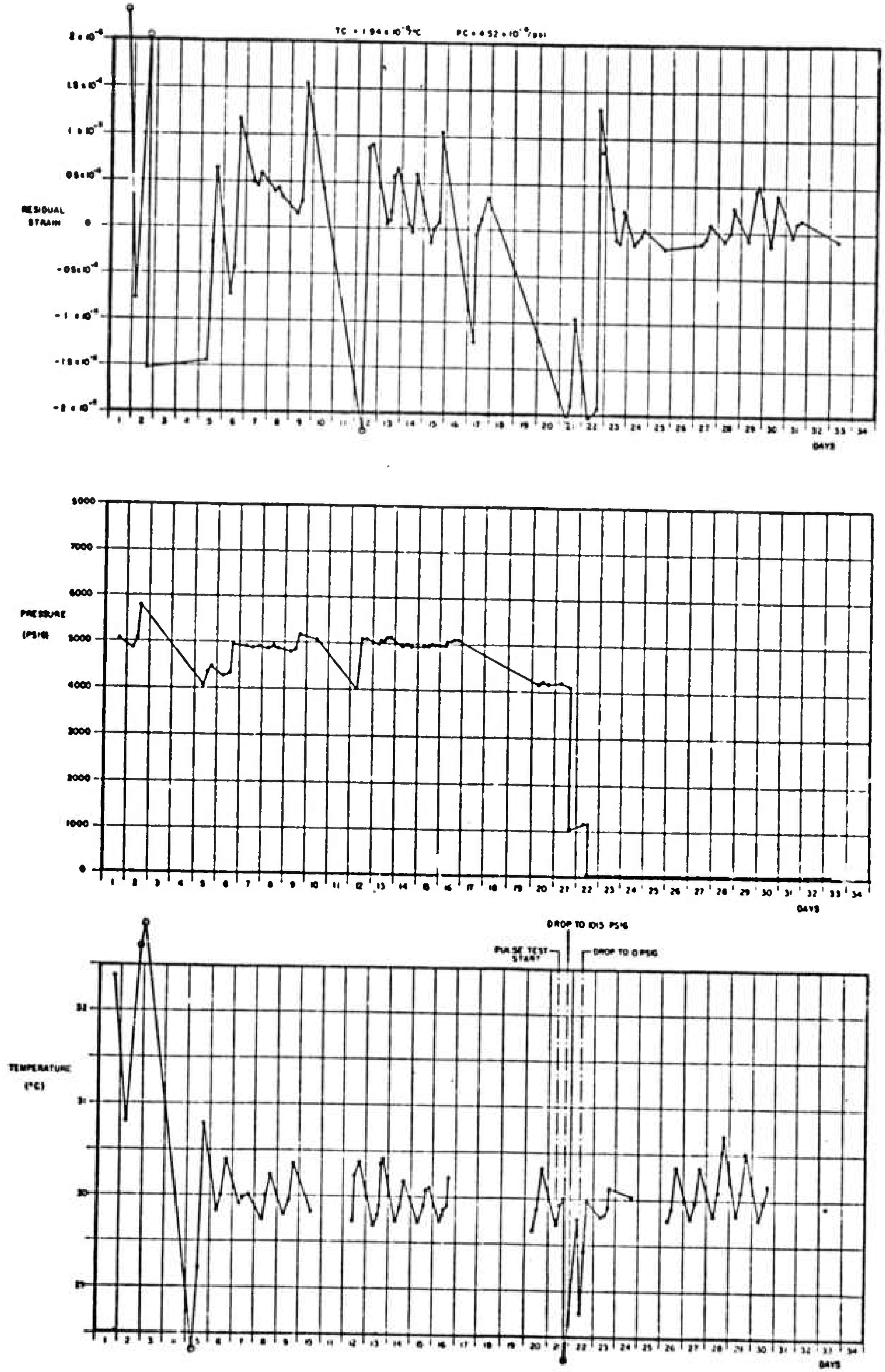


FIGURE 12

LABORATORY MODEL STRAIN SENSOR IN FIXTURE



LABORATORY SENSOR HIGH PRESSURE STABILITY TEST

to operate and to be used for sensor calibration purposes under high pressure conditions.

A 30-day test was conducted in an attempt to evaluate the long-term stability of the strain sensor under high pressure operational conditions. Approximately 1/3 of the test was performed at zero psig for comparison purposes. Since pressure and temperature could not be controlled to simulate actual operational conditions, they were measured and compensated for by statistical analysis techniques. The zero mechanism was not operated to avoid additional mechanical perturbation. Analysis consisted of computing the coefficients of an assumed linear relationship between the dependent variable of strain and the independent variable of pressure and temperature. The computation, based on multiple regression techniques, derives the independent variable coefficients that gives the best fit to the data. The coefficient values of $1.94 \times 10^{-6}/°C$ and $4.52 \times 10^{-9}/psi$ which resulted for the data analyzed are quite consistent with previous results and enhance the technique's credibility.

The difference between the linear prediction and the actual data is the residual strain which is a measure of unexplained performance or noise that may be due to sensor creep, measurement error, or error in the assumed relationships. The rms value of the typical variation which resulted from this analysis is on the order of 2×10^{-7} and is thought to be mostly due to temperature measurement errors caused by gradients. However, the main conclusion to be drawn from this relatively crude experiment and simple analysis is the largest unexplained permanent offset, or time trend, appears to be on the order of 10^{-7}. This seems to be quite good considering the magnitude of the perturbations was on the order of 1000's of psi and several degrees C, which are many orders of magnitude larger than the variations expected to be encountered in actual operation. It is possible that improvement in the analysis could be made by compensating for rates, delays, time, and nonlinearities, but further effort in this area is not considered necessary. In summary, it appears plausible to predict that high operating pressures will have no discernable effects on sensor stability under the stable conditions that are expected in an actual operating environment.

2.2.4 Laboratory Testing

In addition to extensive testing on the prototype and final sensor and electronic subassemblies, a final laboratory test phase was conducted to verify overall strainmeter performance without resorting to simulated environmental conditions, i.e., without grout or a stable temperature environment. All of the laboratory tests were conducted with the strainmeter freely suspended and wrapped with a thin layer of insulation to attenuate ambient temperature effects. Calibration tests were performed using the sensor's zero mechanism which consists of a stepper motor driving the sensor through a gear train and a lead screw arrangement. Each motor step produces the calculated sensor displacement of 1.404 $\times 10^{-7}$ inch per step. The calibrated sensor displacement required to produce a full span chart recording, i.e., ±5 volts amplifier output for the least recording sensitivity, is summarized in Table 3. Full-scale recording sensitivity can be increased by factors of one, two, four, ten, twenty, forty, and one hundred. (Recorder resolution is at least 1/200 of full scale.)

TABLE 3

CALIBRATION DATA

SENSOR	CHANNEL	AVERAGE CALIBRATION (Strain Units)	SATURATION (Volts)
H1A	High Gain	2.34×10^{-6}	+8.0, -8.5
	Low Gain	2.46×10^{-5}	+8.0, -8.5
H2A	High Gain	2.98×10^{-6}	+8.5, -8.0
	Low Gain	3.28×10^{-5}	+8.5, -8.0
H3A	High Gain	1.79×10^{-6}	+8.5, -8.0
	Low Gain	1.79×10^{-5}	+8.5, -8.2
VA	High Gain	1.33×10^{-6}	+8.7, -8.2
	Low Gain	1.52×10^{-5}	+8.5, -8.0
H3B	High Gain	1.20×10^{-6}	+8.5, -8.0
	Low Gain	1.20×10^{-5}	+8.7, -8.2
VB	High Gain	1.40×10^{-6}	+8.8, -8.2
	Low Gain	1.43×10^{-5}	+8.3, -7.9

The displacement values are given in strain units which are based on a 6-1/2 inch horizontal baseline, applicable to the free canister case only, and a 10-inch vertical baseline. (In the installed condition, the effective horizontal baseline may be larger due to the effective strain concentration at the borehole.) Variations in the calibration results from sensor to sensor are due to differences in the sensor manufacturing tolerances and in the downhole electronic gain resulting from the use of fixed components for greater reliability. The values of electronic saturation, included in the table, indicated proper phase adjustment which is necessary to prevent ambiguous results. The data output level between 5 volts and the saturation point may be recorded by the use of the electronic offset which is built into the system.

Tests to determine the strainmeter dynamic behavior were conducted by carefully monitoring sensor output in response to ambient temperature variations as determined by external and internal canister temperature measurements. The temperature variations conveniently produced sensor displacements on the order of 10^{-7} strain units, peak to peak, at a frequency of 2 cycles per hour, or on that order, and larger displacements over longer periods of time. The correlation of sensor response, which was essentially directly due to contraction and expansion of the free stainless steel cylinder, with temperature changes was very good and indicated the strain sensor short-term stability was satisfactory. A check of strain sensor noise, determined by recording samples on the more sensitive ranges, indicated the strainmeter resolution was better than 10^{-9} strain units. It was not possible to obtain a completely satisfactory quantitative determination of strainmeter long-term stability during these laboratory tests; however, the overall test results were satisfactory and it was concluded that a field installation of the strainmeter could be achieved.

2.3 ELECTRONICS DESIGN

The electronic system design approach, Figure 13, was determined by the following goals:

- Provide stable long-term, low level, low noise earth strain measurements
- Operate reliably at great depths and elevated temperatures over an extended period of time in a permanently grouted strainmeter installation
- Provide constant power drain in the strainmeter package to eliminate data errors due to temperature variations.
- Prevent data transmission and processing errors.

To achieve these goals, the complexity of the downhole electronics in the borehole strainmeter canister was reduced to a minimum, and non-adjustable, tested, conservatively operated, high reliability components were used throughout. In addition, the strain sensors are organized in two electrically and physically separate groups for measurement and operational redundancy. High level shielded output signals into high impedance circuits are used, thereby eliminating most common transmission problems. To avoid the use of additional electronics downhole, the current-regulated dc power and the stable reference frequency are transmitted from the wellhead electronics which is located in an instrument room or van at the surface. The wellhead equipment also provides data conditioning and recording equipment.

2.3.1 Downhole Electronics

The strain sensor is a short baseline quartz rod extensometer with capacitance plate sensing elements connected as a full balanced bridge circuit. It is driven by a stable 100-kHz reference signal and produces a low level output signal proportional to sensor deflection. The downhole electronics represents the minimum circuitry to regulate the input, provide low noise amplification, and detect the signals of the strain sensors. Physically, the downhole electronics consists of two different sensor and detector drive regulator subassemblies, and four identical sensor amplifier subassemblies (Figure 14) mounted in three pressure vessel modules per group of four sensors. The electronics modules are located on the uphole side of the strain sensors to minimize lead lengths and thermal convection effects. Operational characteristics are described in Figure 4.

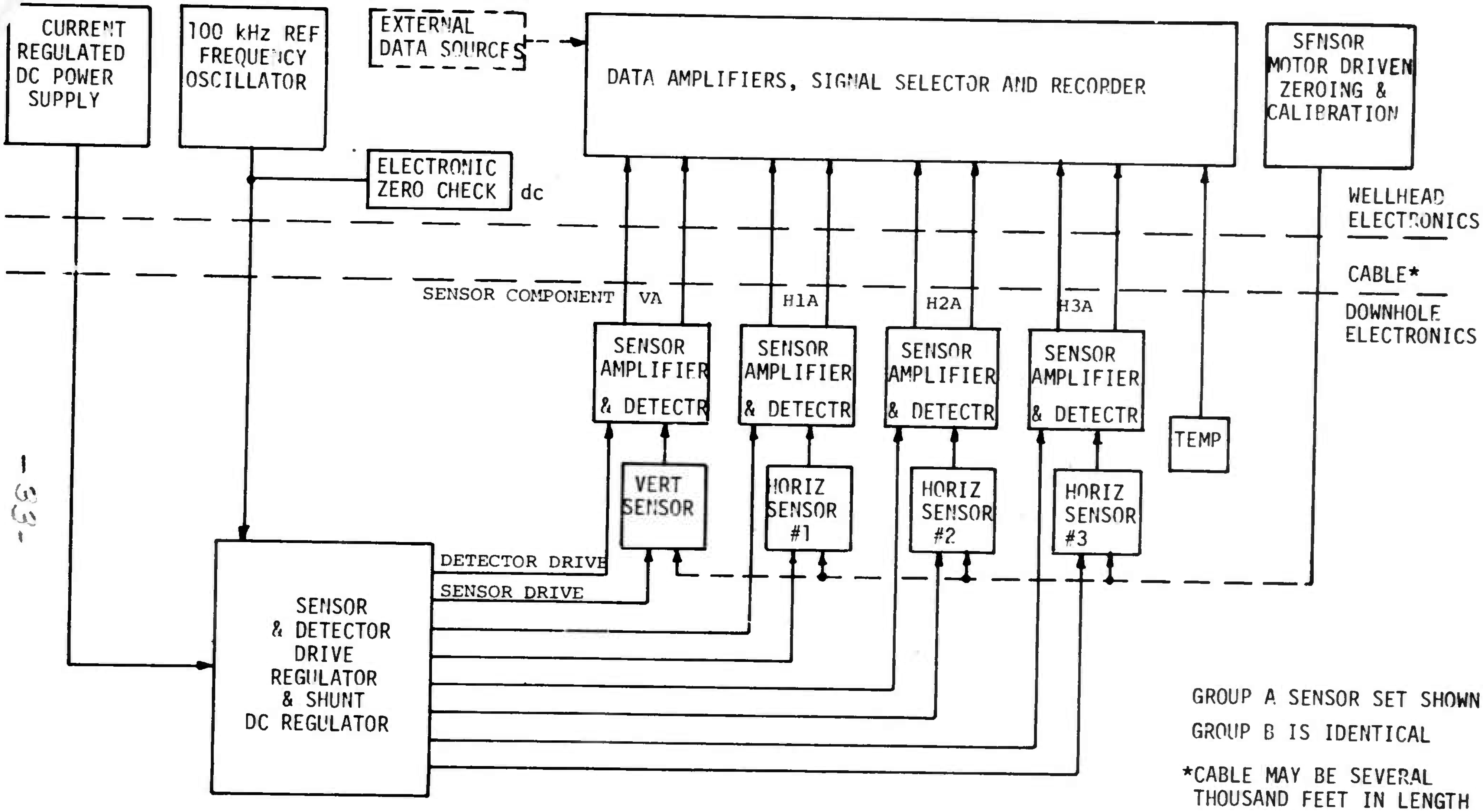


FIGURE 13

ELECTRONICS SYSTEM BLOCK DIAGRAM

TABLE 4

DOWNHOLE ELECTRONICS CHARACTERISTICS

FULL SCALE OUTPUT*	
High Gain Channel	± 5 Vdc/$\pm 10^{-6}$ strain
Low Gain Channel	± 5 Vdc/$\pm 10^{-5}$ strain
MAXIMUM OUTPUT*	±8 Vdc at ±5 mA
OUTPUT RESISTANCE	100 ohms nominal
FREQUENCY RESPONSE	Dc to 100 Hz (Butterworth)
NOISE LEVEL	3×10^{-12} (strain rms)/$\sqrt{Hz}$ (equivalent strain input)
OUTPUT TEMPERATURE COEFFICIENT	
High Gain Channel (±10⁻ strain)	±10 mV/°C (±2 x 10^{-9}strain/°C max)
Low Gain Channel (±10⁻ strain)	±1 mV/°C (±2 x 10^{-8}strain/°C max)
STABILITY	
Long Term (estimated)	±2 x 10^{-9}strain/year
Short Term	< 10^{-9}strain/day
INPUT POWER	
Shunt Regulator Voltage	±16 ±1 Vdc
Input Isolation Resistance	50 ohms
Nominal Input Terminal Voltage	±26 Vdc
Input Current	220 mA per 4-sensor group (nominal)
REQUIRED INPUT CURRENT REGULATION	< ± 0.05%
INPUT REFERENCE FREQUENCY	
Voltage	100 ±50 mV rms (sinusoidal)
Input Resistance	2 kilohms
Frequency	100 kHz ± 100 Hz
Frequency Variation	10 Hz maximum
ZERO CHECK COMMAND	
Zero Command	10.0 ±1.0 Vdc
Normal Operation	0 ± 0.1 Vdc
Input Resistance	4 kilohms
OPERATING TEMPERATURE	+25 to +125°C
STORAGE TEMPERATURE	-20 to +150°C

*Nominal;actual value depends on individual sensor calibration. Positive signals correspond to compressive strain. All parameters referenced to the strainmeter instrument package connector.

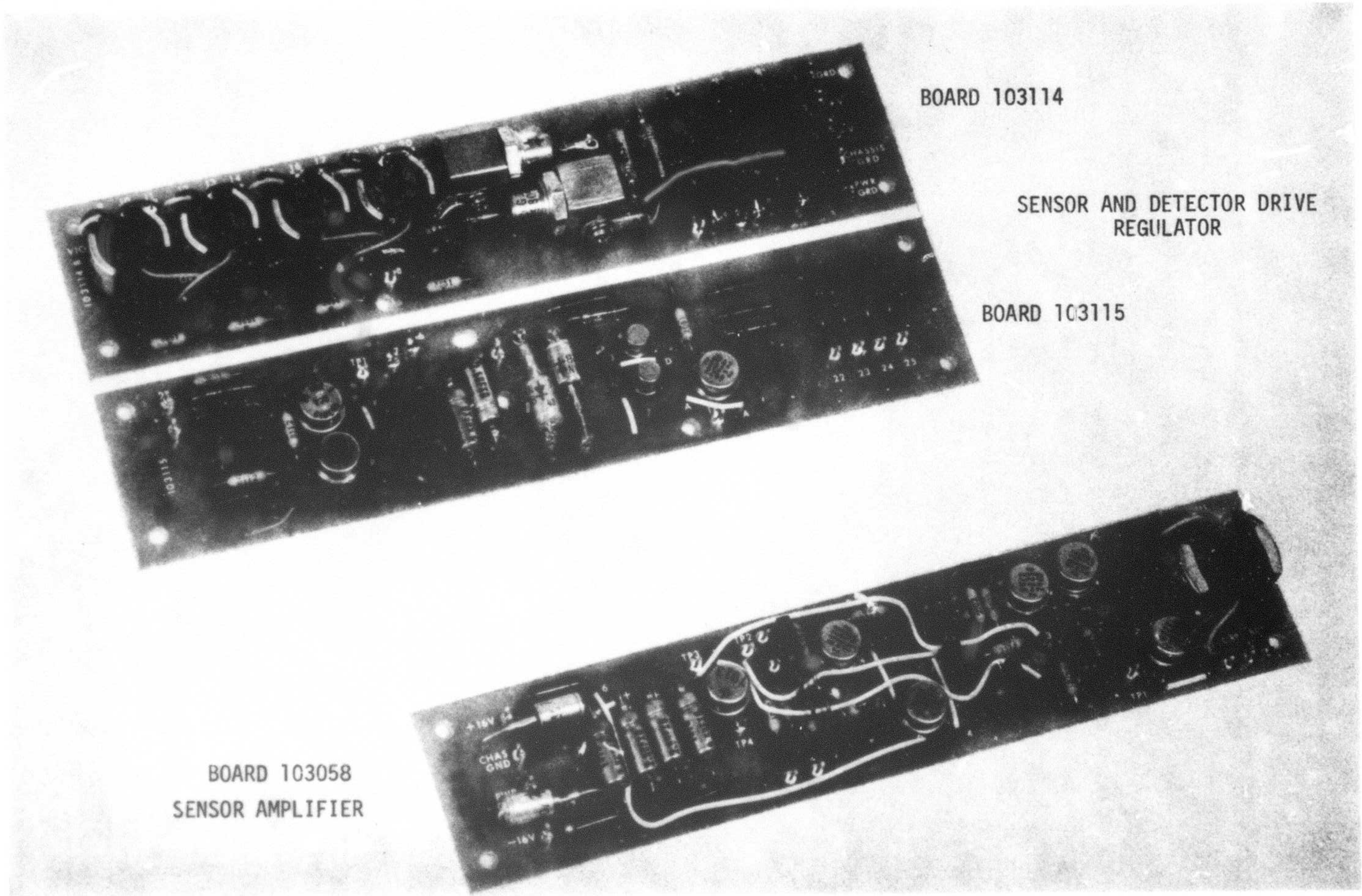


FIGURE 14

DOWNHOLE ELECTRONIC SUBASSEMBLIES FOR ONE GROUP OF SNESORS

The sensor and detector regulator circuitry controls and distributes the dc current regulated input power and 100-kHz sensor reference frequency, both of which are transmitted from the wellhead system. A dc shunt regulator operates in conjunction with the regulated input current to control input power, maintaining an even temperature and regulated voltage. The transmitted oscillator signal is amplified, symmetrically limited, regulated, and distributed to the input of the individual strain sensors through transformers. Stray coupling of the 100-kHz signals was not a problem since good shielding practice was followed.

The sensor amplifier circuitry amplifies and detects the 100-kHz strain sensor signal output. The first stage is a low input impedance preamplifier and first amplifier to raise the signal level and minimize temperature effects of the coupling transformers. The signal is split into two channels, one of which provides an additional 20 dB or gain, to provide output ranges of $\pm 10^{-5}$ and $\pm 10^{-6}$ strain. The ac signals in each channel are then processed by a dual channel coherent detector which takes its reference from the sensor drive signal. Phase shifts are carefully balanced. This technique is inherently linear and eliminates the need for a post detection, high-gain dc amplifier with its attendant stability limitations.

The high level detector outputs drive 100-Hz active low pass filters to produce the analog signals that are transmitted directly to high impedance amplifiers at the wellhead system for each sensor channel. Additional complexity and unreliability caused by multiplexers, ac or FM transmission is thereby avoided. High level signals also eliminate first-order effects due to the initial or time-varying conditions of the cable. This approach complicates the downhole cable but is considered optimum in terms of the overall reliability and cost for applications involving a permanent nonrepairable emplacement.

2.3.1.1 Sensor and Coupling Network Operation

Figure 15 shows the strain sensor, connected as a capacitance bridge, being driven with a stable 100-kHz sinusoidal reference signal. The

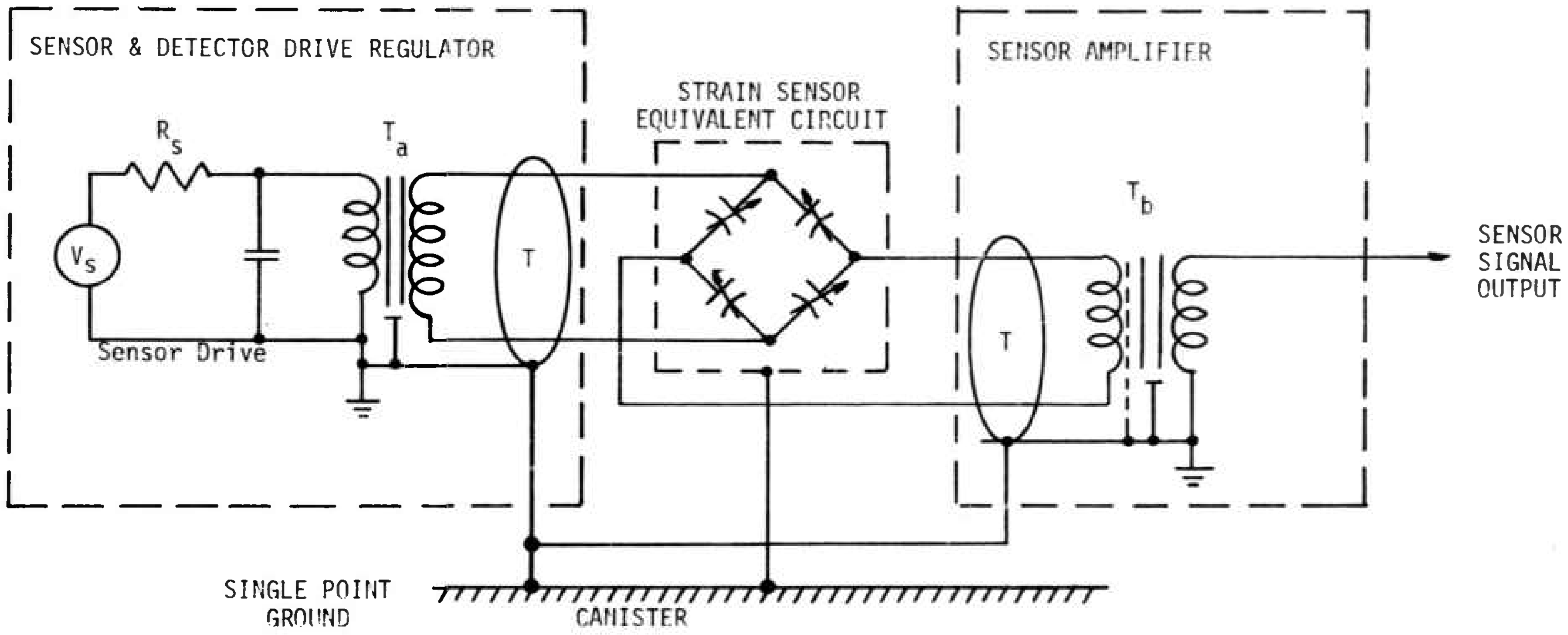


FIGURE 15

SENSOR AND COUPLING NETWORK SCHEMATIC

bridge output-to-input voltage ratio is KD/d times the rock strain. (Refer to the Appendix) K is the magnification of strain provided by the borehole, D is the sensor baseline and d is the capacitor plate spacing (sensor centered). For a baseline of 6 inches, spacing of 0.006 inches and hole magnification of 1.5, the voltage magnification will be 1500 times the rock strain.

The maximum drive level is determined by the allowable dissipation in the sensor due to dielectric and other losses and the preamplifier noise level. A conservative limit of 25 microwatts for the sensor drive dissipation was chosen on the basis of thermal calculations. A voltage of approximately 1 volt rms applied to the drive transformer insures the maximum dissipation will not be exceeded under worst-case conditions. With a drive transformer ratio of unity, a sensor bridge output-to-input ratio of 1.5×10^{-6}, and signal transformer ratio of approximately 5.75:1, there will be an equivalent preamplifier input signal of approximately 5×10^{-4} volt rms for 10^{-9} strain (after cable attenuation and the preamplifier feedback are taken into account). This signal level is well above the input noise level of the integrated circuit operational amplifier which is 5×10^{-7} volt in a 100-Hz bandwidth.

The input drive transformer, T_a, and the shunt primary capacitance form a single-pole filter with a resonant frequency of 100 kHz and a Q of 10. This filters the square wave signal from the drive regulator and supplies the signal to the sensor in sinusoidal form. The output impedance of this circuit is approximately 3 kilohms. Since the sensor input impedance is approximately 13 kilohms, this represents a relatively low impedance source which minimizes the effects of inductance changes due to temperature variations.

Inductance of the output signal transformer, T_b, is designed to resonate at 100 kHz with the net bridge capacitance of 45 picofarads, the cable capacitance of 60 picofarads (3 feet of Belden 83317) and the transformer self capacitance of 14 picofarads. The

transformer itself is wound to minimize self capacitance and has a Q of 180. Thus, the resonant network by itself is high Q to optimize circuit noise performance. However, heavy feedback is employed in the preamplifier to reduce the input impedance and, thus, reduce the input Q to approximately 3.6, which also serves to minimize the effect of inductance changes. The step-down winding ratio of 5.74 to 1 presents the optimum source impedance to the preamplifier.

Since the signal phase determines the polarity of the output signal, the winding and connection sense of all transformers must be consistent for all sensor channels.

This fully balanced structure is first-order insensitive to changes in the dielectric constant of the fluid in which the sensor is immersed, to the drive frequency stability and to the stability of the transformer inductance. The electronic noise, and therefore resolution, will be affected by these parameters, but they will not introduce first-order strain errors because the drive voltage and frequency is regulated and the signal output is heavily damped by preamplifier feedback. The sensor drive frequency is somewhat arbitrary. However, the value of 100 kHz was chosen as offering the best compromise among circuit parameters such as transformer size, stray coupling, amplifier performance and distributed effects. Also note that single point grounding was used for all electronic subassemblies to minimize interference.

The maximum displacement range of the sensor bridge is ± 0.004 inch and the plate spacing is 0.006 inch. However, the nominal electronic range is $\pm 10^{-5}$ strain which is roughly equivalent to a displacement of ± 0.0001 inches. The theoretical linearity of the bridge output over this range is better than 1%.

2.3.1.2 Sensor and Detector Drive Regulator Operation

The strain sensor requires an amplitude regulated, long-term stable drive signal for the instrument sensitivity, accuracy and stability objectives to be met. The sensor output signal is coherently, or synchronously, detected which requires a detector drive signal that is in phase with the sensor drive signal. Further, the relatively high power dissipation of the electronic circuitry must be maintained constant to avoid temperature variations that will cause strain measurement errors. These functions are provided by the sensor and detector drive regulator circuitry illustrated in Figure 16.

The 100-kHz sensor reference frequency is generated by the wellhead system crystal oscillator which has a frequency stability of better than ±0.01% over the expected temperature range. The reference signal is transmitted downhole in low level sinusoidal form. The lines are adequately shielded in the downhole cable to prevent interference problems. Attenuation of the 100-kHz signal in the downhole cable is approximately 20 dB in 2000 feet. The wellhead oscillator output can be adjusted to insure the required signal level of 0.100 ±0.05 volts rms is attained at the regulator input.

Amplification and symmetrical limiting of the reference signal is provided by amplifier A1, and feedback limiting diodes DA1, which has a gain of 40 dB and produces a 2-volt peak-to-peak output. The resulting square wave is amplitude regulated by zener diode CR1 and amplitude controlled by amplifier A2 to produce a sensor drive level of 2.75 volts p-p. Odd harmonics of the square wave are rejected by tuned sensor drive transformer primary tank circuits with a Q of 10. The resulting sinusoidal sensor signal of approximately 1 volt rms is coupled to each sensor through individual transformers for redundancy and isolation. A square-wave signal of 11.4 volts p-p for the coherent detector drive is taken directly from CR1. The detector drive signals for each sensor channel are decoupled from each other by resistors R15 to R18.

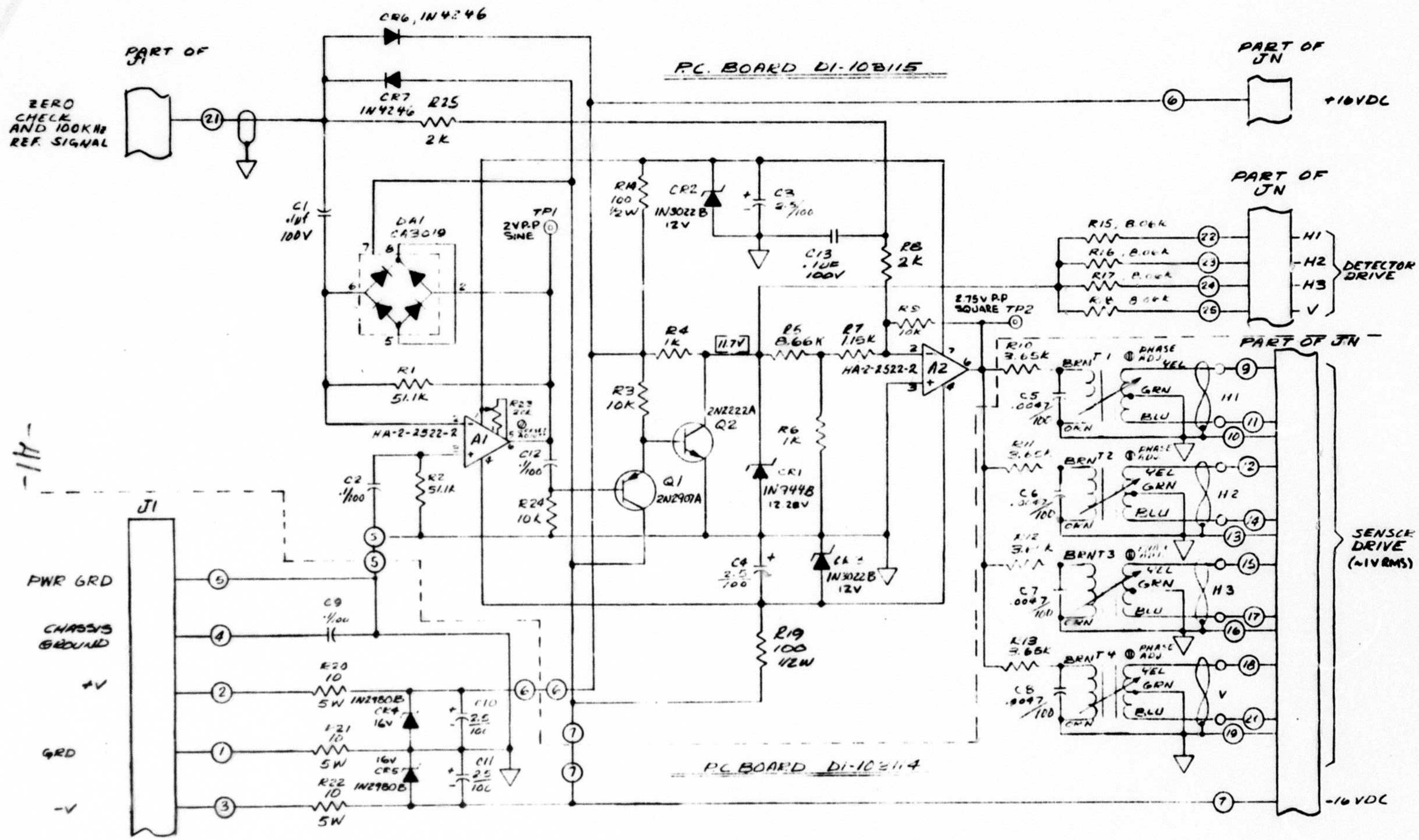


FIGURE 16

SENSOR AND DETECTOR DRIVE REGULATOR

A dc control voltage to turn off amplifier A2, as a command from the wellhead system, is multiplexed on the downhole cable conductors carrying the reference signal. This allows the sensor drive to be turned off while the coherent detector is still operational, thus permitting a check on the output offsets (i.e., electronics zero) of the sensor amplifiers. The voltage required at the circuit terminals is 10.0 ±1 volts for OFF (electronic zero) and 0 ±0.1 volt for ON (normal operation).

The total electronic power dissipation, for two groups of eight sensors, is on the order of 10 to 20 watts which principally results from the relative inefficiency of the simple regulators required. The medium power operational amplifiers chosen to meet performance and reliability requirements at a 125°C maximum operating temperature also contribute. This will result in a strainmeter temperature rise of 1 to 2°C. To insure a temperature stability on the order of a millidegree C from this source, the current regulation must be on the order of 0.05% with a constant input voltage.

The wellhead dc power supply furnishes a regulated current of approximately 220 milliamperes downhole for each sensor group. At this current level, a cable voltage drop of approximately 4 volts occurs per 1000 feet and the wellhead supply voltage is adjusted accordingly. A shunt regulator, consisting of zener diodes CR4 and CR5, clamps the dc input at ±16 ±0.8 volts and establishes the downhole circuit ground. (Refer to Section 2.3.3 for details on conditions as installed.) The combination of current regulation and the shunt regulator serves to maintain the required constant power drain. Further voltage regulation is provided by the independent reference zener diodes CR2 and CR3. Regulated power is distributed through terminals 6 and 7 to the individual sensor amplifier assemblies which also contain independent reference diodes.

Decoupling of inadvertent overvoltages on the downhole cable lines, such as may result from lightning or RFI, is provided by diodes CR6 and CR7 to the power supply lines. Protection of the dc power sec-

tion from overvoltage conditions on the downhole cable is implicit in the shunt regulator. Although the primary protection circuits are located at the wellhead and the cable is shielded, these features provide an additional stage of protection for the circuitry.

2.3.1.3 Sensor Amplifier Operation

The low level, 100-kHz output from each strain sensor is amplifier and detected by an individual sensor amplifier circuit, illustrated in Figure 17.

The strain sensor and primary of transformer T1 comprise a tuned tank circuit whose resonant impedance is transformed to present the optimum source impedance to preamplifier A1:

$$Z_{OPT} = \frac{Q_T X_L}{N^2}$$

where Z_{OPT} = the optimum source impedance
Q_T = the tank Q
X_L = primary reactance at resonance
N = secondary-to-primary ratio

The optimum source impedance is approximately 35 kilohms and the circuit parameters were chosen to provide this impedance.

Capacitor C18 and resistor R24, between ground and the amplifier A1 bandwidth control, provide constant open loop gain at 100 kHz and thereby a constant input impedance for A1. The input impedance, which is the ratio of open loop gain and feedback resistance R13, is transformed back into the primary tank of T1, reducing its Q to approximately 3.6. The low Q assures that inductance changes due to temperature variations become second-order effects. The gain of A1 is approximately 10 dB.

The gain of amplifier A2 is chosen such that its output is 10 volts p-p with a strain magnitude of 10^{-5} for the exact voltage magnification of each sensor and the specified drive level. (Since thermal gradients on the order of millidegrees are not to be exceeded,

the sensor drive power, and therefore drive level magnitude, will remain fixed.) The signal is split into two channels to provide nominal output ranges of $\pm 10^{-5}$ and 10^{-6} strain. The amplifier A3 raises the signal level an additional 20 dB for the 10^{-6} strain output. This is done prior to detection to eliminate a dc amplifier and its inherent stability limitations.

Synchronous detection is employed since the direction of strain must be known. The detection of the signals in each channel is performed by the dual channel analog switch S1. The strain signal input to the detector and detector drive are adjusted to be in phase by adjusting the inductance in the appropriate transformer of the sensor and the detector regulator circuit for each sensor. Dc coupling into the detector is used for simplicity. Temperature compensation has been found to be unnecessary.

An active lowpass Butterworth filter of approximately 100-Hz bandwidth and gain of π follows the detector. The filtering serves to attenuate spurious signals transmitted down the cable. The resulting ±5 volt full scale analog signals are transmitted directly to high impedance amplifiers at the wellhead. However, the output signal is linear up to the point of amplifier saturation at ±7.5 to 8 volts. The amplifier saturation level will remain essentially fixed regardless of further increases in signal. Protective diodes are used on the outputs of all amplifiers driving data topside, again, to provide overvoltage protection for the circuit.

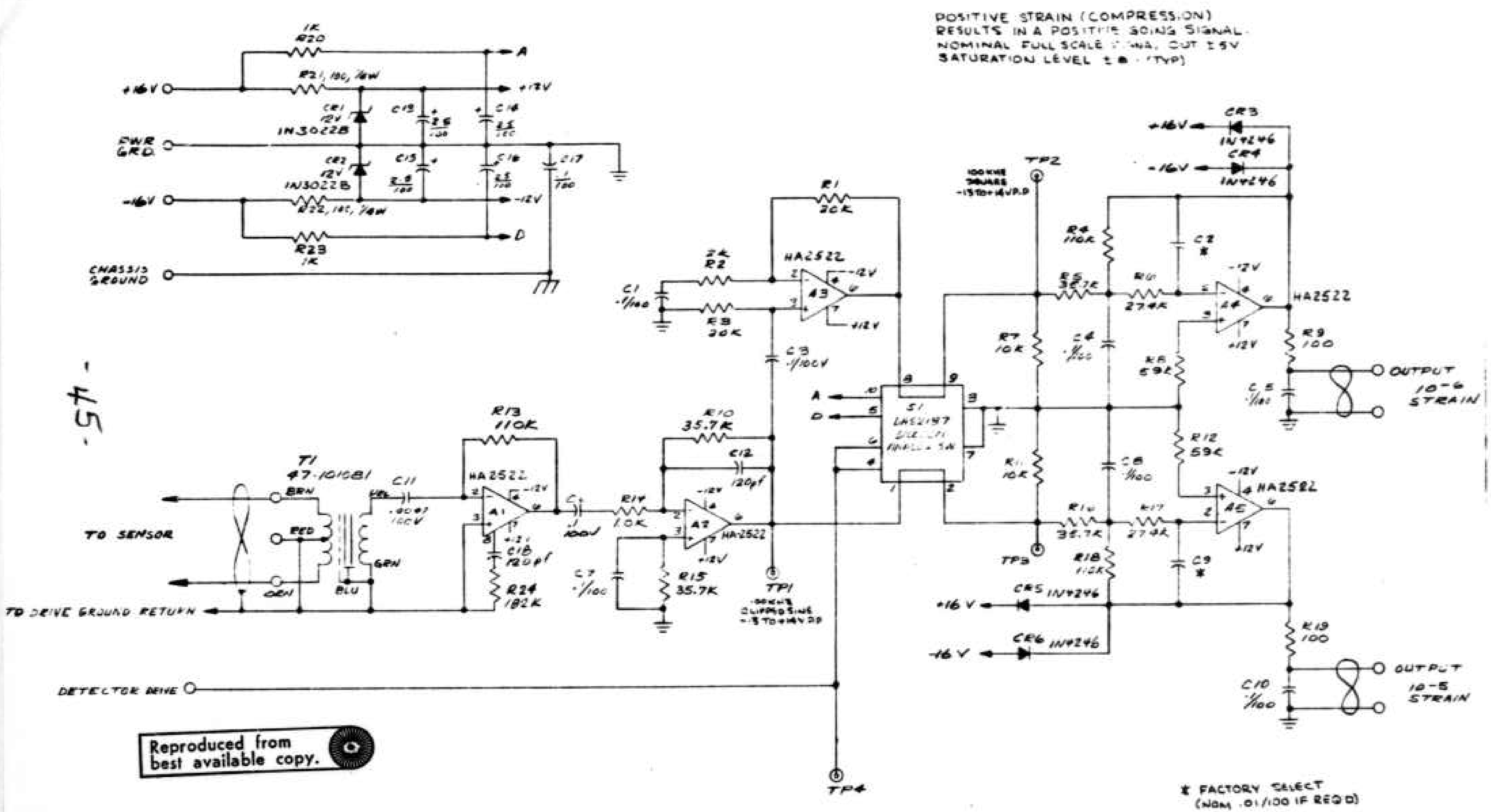


FIGURE 17

SENSOR AMPLIFIER CIRCUIT

2.3.2 Wellhead Electronics

The wellhead electronics system, Figure 18, is standard instrumentation located in an instrument room or van at the surface. This equipment provides dc power, reference signals and controlled stepper motor power for sensor zeroing and calibration, to the strainmeter instrument. The amplifier and recorder sections provide signal processing, strainmeter temperature monitoring and the potential for any type recording, although a multipoint paper chart recorder was used for the first system. Considerable flexibility has been built into the equipment to facilitate field use. For example, signal monitoring, amplifier self check and means for patching in external data sources have been provided. With appropriate compensation for cable power losses, this equipment could be located up to several thousands of feet away from the strainmeter.

2.3.2.1 Amplifier Section

The wellhead strainmeter amplifier, Figure 19, is a dc coupled high impedance differential input, single-ended output unit to provide stable signal conditioning. Operational characteristics are given in Table 5. Considerable flexibility is provided to facilitate its use with strain sensor or auxiliary inputs for manual, analog and digital recording or data transmission equipment. Eight channel amplifier modules are located in each rack-mountable chassis.

The circuit, Figure 20, consists of three stages of basically unity-gain amplifiers designed so they cannot fold back when overdriven. The first stage filtered differential input provides a high degree of RFI and common mode rejection. In addition, the gain of this stage, A1, is internally switch selectable to provide x1 (normal), x10 or an optional third gain. The output of this stage could be used for digital recording of broadband data, i.e., up to several thousand hertz, depending on the source.

Amplifier stage A2 provides switch selectable lowpass filtering with bandwidths of 0.05 and 10 hertz that rolls off at 12 dB per octave. However, other bandwidths may be achieved with simple component changes.

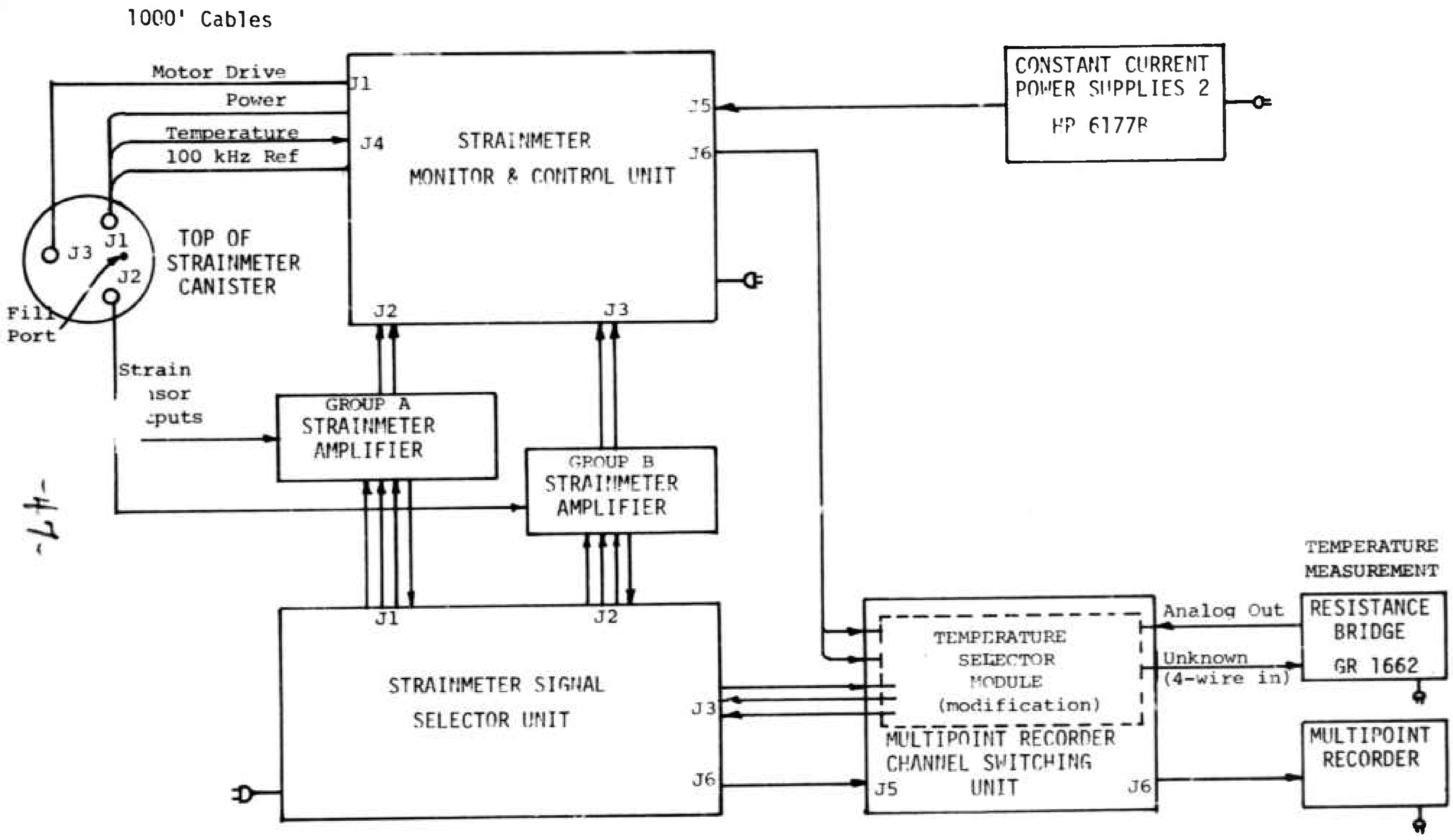


FIGURE 18

BOREHOLE STRAINMETER WELLHEAD SYSTEM BLOCK DIAGRAM

TABLE 5

STRAINMETER AMPLIFIER OPERATING CHARACTERISTICS

INPUT LEVEL	±5 V nominal full scale ±15 V maximum linear range ±30 V is fault limit
INPUT RESISTANCE	1 megohm (500 kilohms balanced to ground)
VOLTAGE GAIN	Switch selectable 1 and 10 ±10% adjustable
OUTPUT LEVEL	±5 V nominal full scale

OUTPUT ATTENUATOR (SPAN)

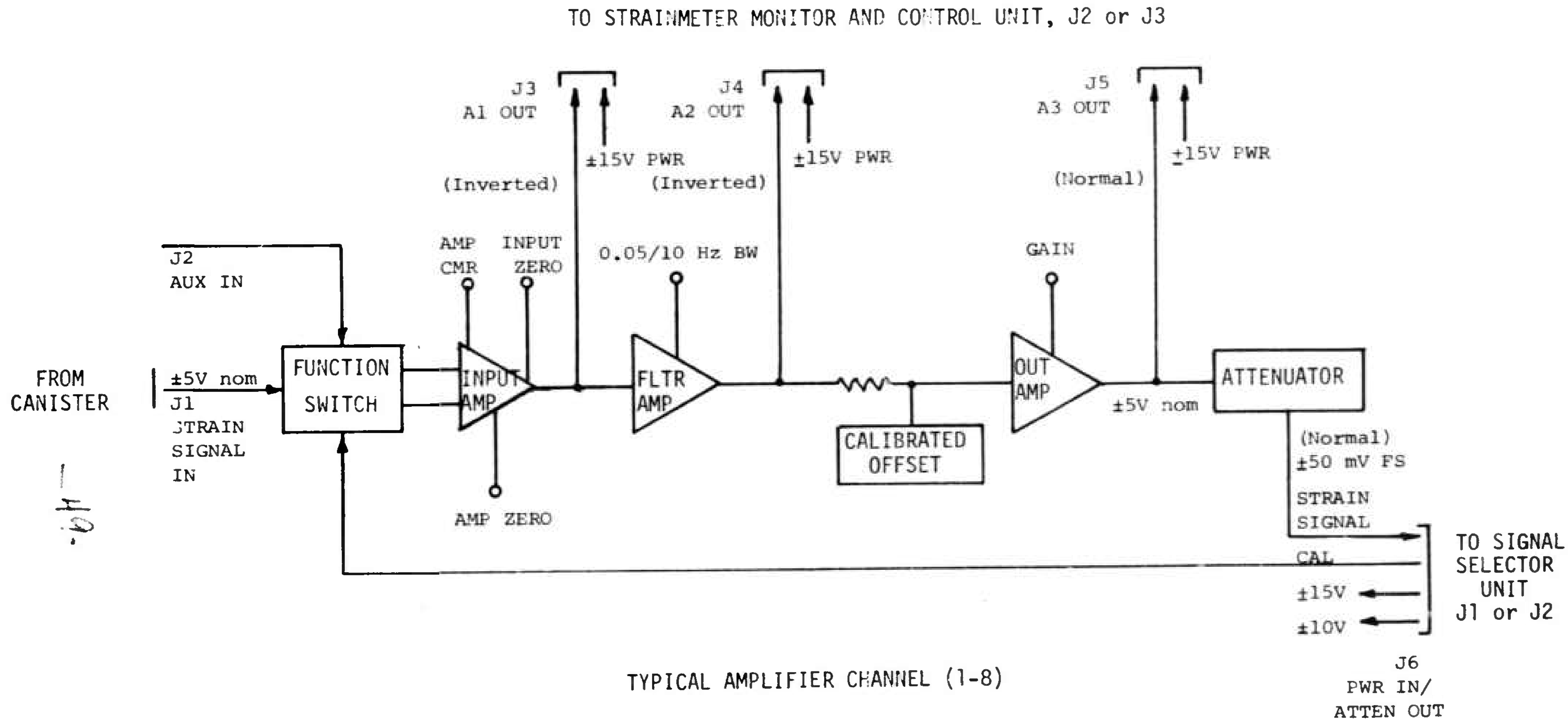
(Attenuator is for use with analog recorder only. Analog recorder input is ±50 mV full scale. Digital system output bypasses the attenuator.)

These are nominal strain units and must be multiplied by the scale factor for each sensor or to adjust the amplifier gain to compensate for scale factor variations.

RECORDER FULL SCALE STRAIN High Gain	Low Gain	VOLTAGE ATTEN
0.2×10^{-7}	0.2×10^{-6}	1
0.5×10^{-7}	0.5×10^{-6}	2.5
1×10^{-7}	1×10^{-6}	5
2×10^{-7}	2×10^{-6}	10
5×10^{-7}	5×10^{-6}	25
10×10^{-7}	10×10^{-6}	50
20×10^{-7}	20×10^{-6}	100

INPUT OFFSET RANGE	±5.5 Vdc. External, noncalibrated, continuously adjustable. Has front panel test point.
OUTPUT OFFSET RANGE	±5 Vdc External control, adjustable in 50-mV steps. Calibrated in terms of nominal strain units.
OFFSET LINEARITY	±0.03% of span
BANDWIDTH	Dc to 0.05 Hz and dc to 10 Hz 12 dB/octave rolloff above 0.05 Hz and 10 Hz. Switchable on the front panel. May be modified to other values by replacing 2 components.
OUTPUT NOISE	15 μV p-p (0.01 to 10 Hz) referred to input
OUTPUT DRIFT	1 mV/month and 60 μV/°C referred to input This represents a worst-case data uncertainty of 5×10^{-10} strain, on the low range, over 0 to 50°C and one week.

NOTE: Positive voltage at the input corresponds to positive, i.e., compressive, strain.



TYPICAL AMPLIFIER CHANNEL (1-8)

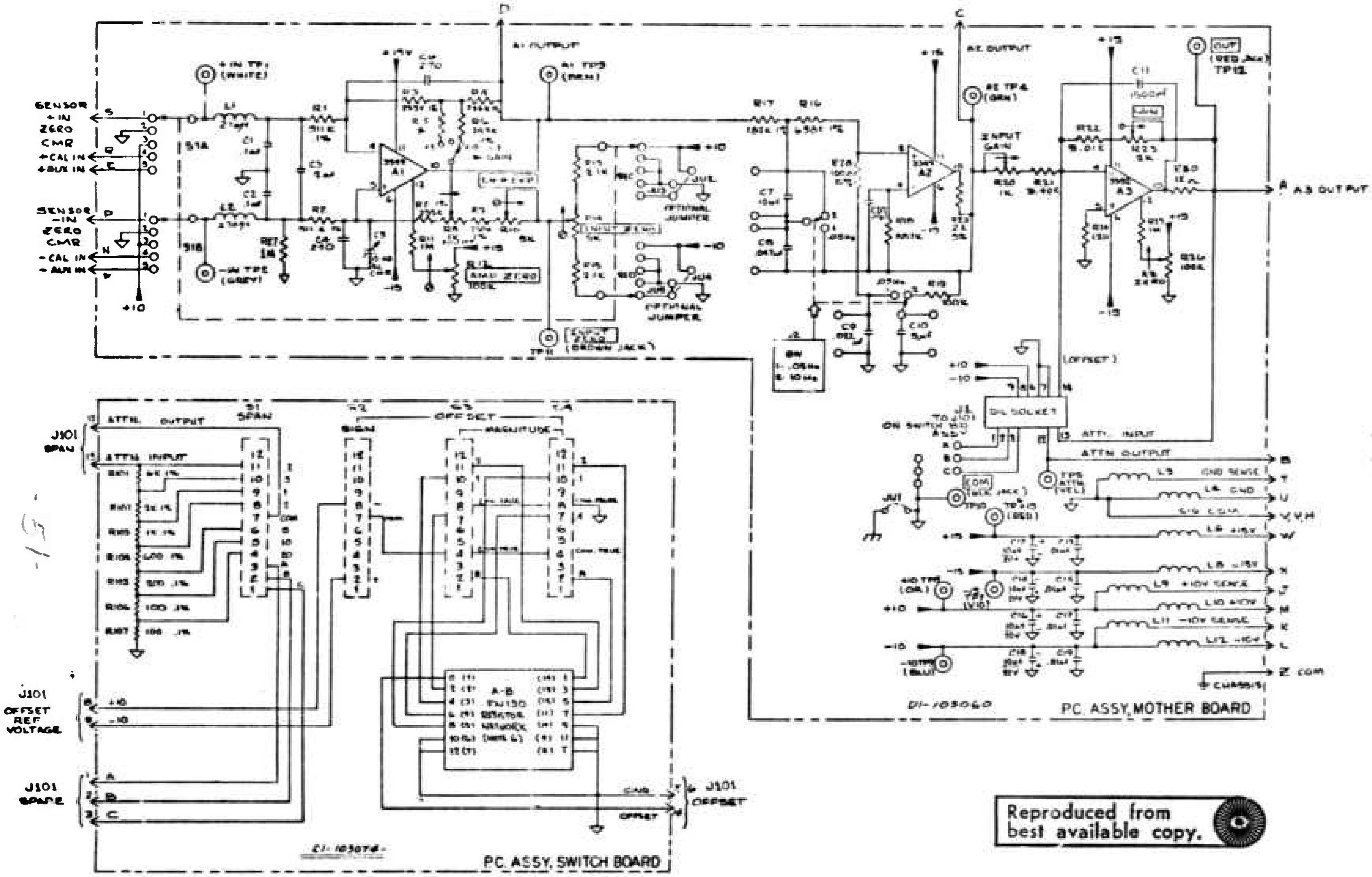
FIGURE 19

STRAINMETER AMPLIFIER BLOCK DIAGRAM

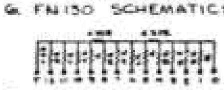
The output of this stage could also be used for digital recording or to drive a voltage-controlled oscillator (VCO) for telemetry purposes.

Outputs from amplifier stage A3 are intended for analog or digital recording and other reference functions. The switch-selectable calibrated offset is used to keep the recordings on scale when the signal is greater than nominal full scale or for higher recording sensitivities. This function could be modified for electronic operation in remote control applications. The calibrated span (attenuator) control provides a ±50 mV full-scale output for direct recording on the multipoint chart recorder at various sensitivities.

The amplifier also has a combination of vernier zero and gain adjustments. Zero controls are used to compensate for internal amplifier or sensor input offsets. The gain controls are used to achieve exactly unity gain or to compensate sensor scale factor deviations of up to ±10% from nominal. Figure 21 shows the front panel of the strainmeter amplifier unit.



NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL RESISTORS TO BE 1/2 W, 1%, METAL FILM
2. ALL INDUCTORS TO BE 270μhy
3. ----- DENOTES PC BOUNDARY
4. ◎ DENOTES TEST POINT
5. S1 AMP CHECK:
   1. OPERATE
   2. ZERO
   3. CMR
   4. GAIN
   5. AUX INPUT (NOT LABELED ON FRONT PANEL)
6. FN130 SCHEMATIC:



7. * FACTORY SELECTED
8. L3 - L12 NORMALLY JUMPERS. OPTIONAL - MAY BE SAME AS L1 & L2
9. INDICATES FRONT PANEL OUTPUT - ☐

FIGURE 20

STRAINMETER AMPLIFIER

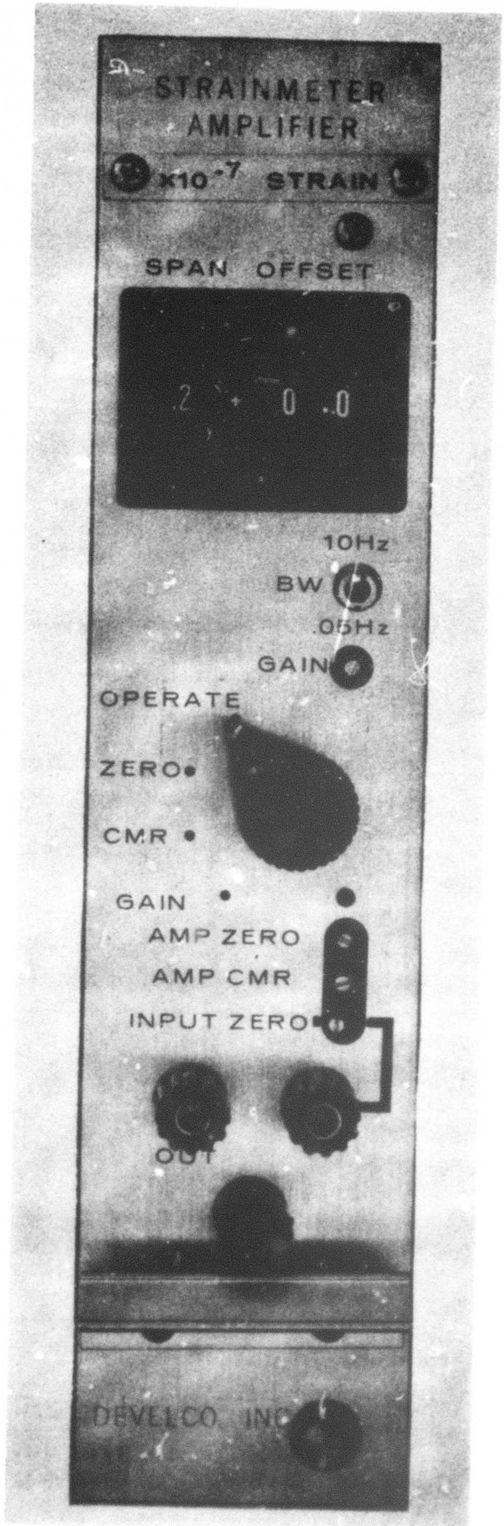


FIGURE 21

STRAINMETER AMPLIFIER FRONT PANEL

2.3.2.2 Recording Section

The recorder used in the prototype system is a Leeds and Northrup Model Speedomax W multipoint potentiometric recorder with null balance. It can print out data from up to 24 selectable input channels at a sample rate of once every three seconds. The chart width is approximately 10 inches and is divided into 100 minor divisions. The electrical sensitivity is 100 mV for full scale with zero center capability but fault protection up to ±30 V is provided. Overall recorder accuracy is 0.3% of span with a dead band of less than 0.15% of span and essentially no drift.

The chart speed is variable from a rate of one inch per hour to 120 inches per hour in 10 increments. The one-inch-per-hour rate is typically used and, at this rate, 45 days of operating time can be achieved per roll of paper. Physically the recorder is split up into two separate units. One contains the recorder mechanism and power supplies and the other contains the timing circuitry and relays for multiplexing between the input channels and controlling the printing operation. The switching unit is also used to provide timing inputs to the strainmeter temperature selector module.

Chart speed is controlled by a synchronous motor and is sufficiently accurate for immediate purposes. Also, since the event marker provided was not reliable, it proved adequate to manually mark WWV time on the chart at convenient intervals. Overall recorder performance has been satisfactory and reliable.

The Signal Selector unit was provided to facilitate switching the various data channels to the multipoint recorder input channels in any combination. The cross bar switch used to accomplish this patching operation is limited to 20 channels, so recorder channels 21 through 24 are wired in parallel with channels 9 through 12. Provisions have also been made for patching auxiliary inputs such as external temperature or data from surface strainmeters into the recorder through the switch. This rack-mounted unit also contains the power supplies and regulators for supplying the data amplifier units with power, reference, and calibration voltages. It also provides ±15 V power to other units.

2.3.2.3 Strainmeter Temperature Measurement Section

Since the strain sensor output is expected to be a fairly sensitive function of the strainmeter temperature, an accurate and reliable method of making sensitive temperature measurements was required. The technique chosen was developed by USGS for borehole logging applications, such as heat flow and water flow studies, which require accurate and repeatable measurements. The original method used a specially constructed thermistor temperature probe and a 4-wire Wheatstone bridge to accurately measure the resistance changes as a function of temperature. This technique has proven capable of measuring temperature changes of less than 1 m°C with a stability of better than 1 m°C per month in logging applications. It is estimated to be capable of considerable better stability in static applications.

The probe used is the Fennwall Electronics Co. Model K212E multiple bead thermistor assembly, mounted and potted in a small diameter stainless steel tube assembly which is capable of direct exposure to fluid pressures of several thousands of psi. It has been found that a probe resistance of 10-12 kilohms at the center of the temperature range of interest is optimum for these measurements which require about 20 beads at 20°C. Since the coefficient is on the order of 1 kilohm but slightly nonlinear for large changes, a probe with resistance adjusted to approximately 100 kilohm at 25°C should be used for temperature measurements around 80°C. Probes are supplied from the factory calibrated from 0°C to 180°C to within ±0.1 °C, but can be recalibrated using special techniques to achieve an accuracy of better than ±0.1 m°C.

A General Radio Model 1663 Resistance Limit Bridge was chosen for this system because of features that were more suitable for long-term recording of small changes. It is a 4-wire kelvin bridge with a null detector, recorder output and 5 calibrated deviation ranges with full scale outputs from ±0.3% to ±30% of the resistance setting. Thus, a full scale recording of temperature changes as small as 150 m°C can

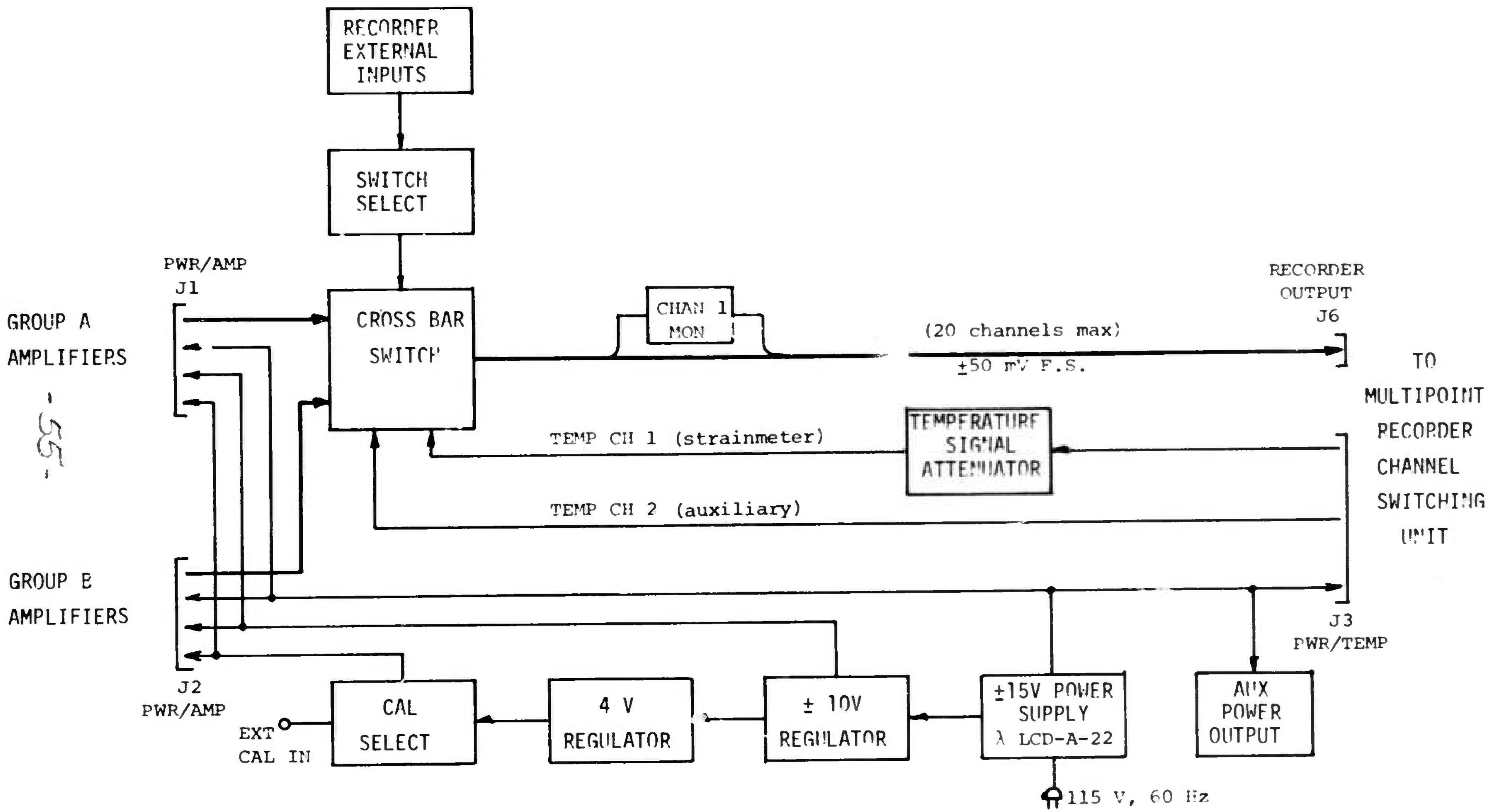


FIGURE 22

BLOCK DIAGRAM

STRAINMETER SIGNAL SELECTOR UNIT

be achieved. The bridge excitation level is such that the probe dissipation is approximately 0.3 μW or 1 μW, with the bridge set to x 0.1 or x1 resistance multipliers respectively. The probe self-heating from the higher level results in a temperature rise of less than 1 m°C so it is ignored for practical purposes, although time is allowed for thermal settling after switching.

The estimated absolute accuracy of this approach is only 5 to 20 m°C including other factors such as cable and matching effects; however, the relative measurements are principally of interest and, for these, the deviation accuracy results in an error of less than 1 m°C. Although the method is very promising for the application, the actual results were poor due to the tendency of the photochopper in this bridge design to become unstable after a very short period of time.

Two temperature probes were used in the strainmeter canister for redundance and to estimate gradients. To permit automatic switching between them, the Temperature Sensor Selector module was added to the Recorder Channel Switching Unit, Figure 23. The Temperature Sensor Selector Module is basically a relay switch to connect one of the two sensors to the resistance bridge and for reversing the leads to the sensor to check the thermal emf generated in the cable leads, which could result in an error as large as 3 m°C per 1000 feet. Mercury-wetted relays are used for low contact resistance, low thermal emf, and to insure there is no leakage current into the sensor from the relay coil. The selector can be electronically or manually switched. The electronic switching signals are derived from the recorder power applied to the individual input relays which makes it possible to program the selector to switch when the recorder switches to a specific channel. The programming sequence for the full automatic mode of operation is summarized in Table 6. This sequence samples each probe every six points or 18 seconds with two samples per probe, and allows sufficient time between switching and reading. If cable effects are not significant, the selector can be programmed to automatically switch between sensors without polarity reversal. When using both probes

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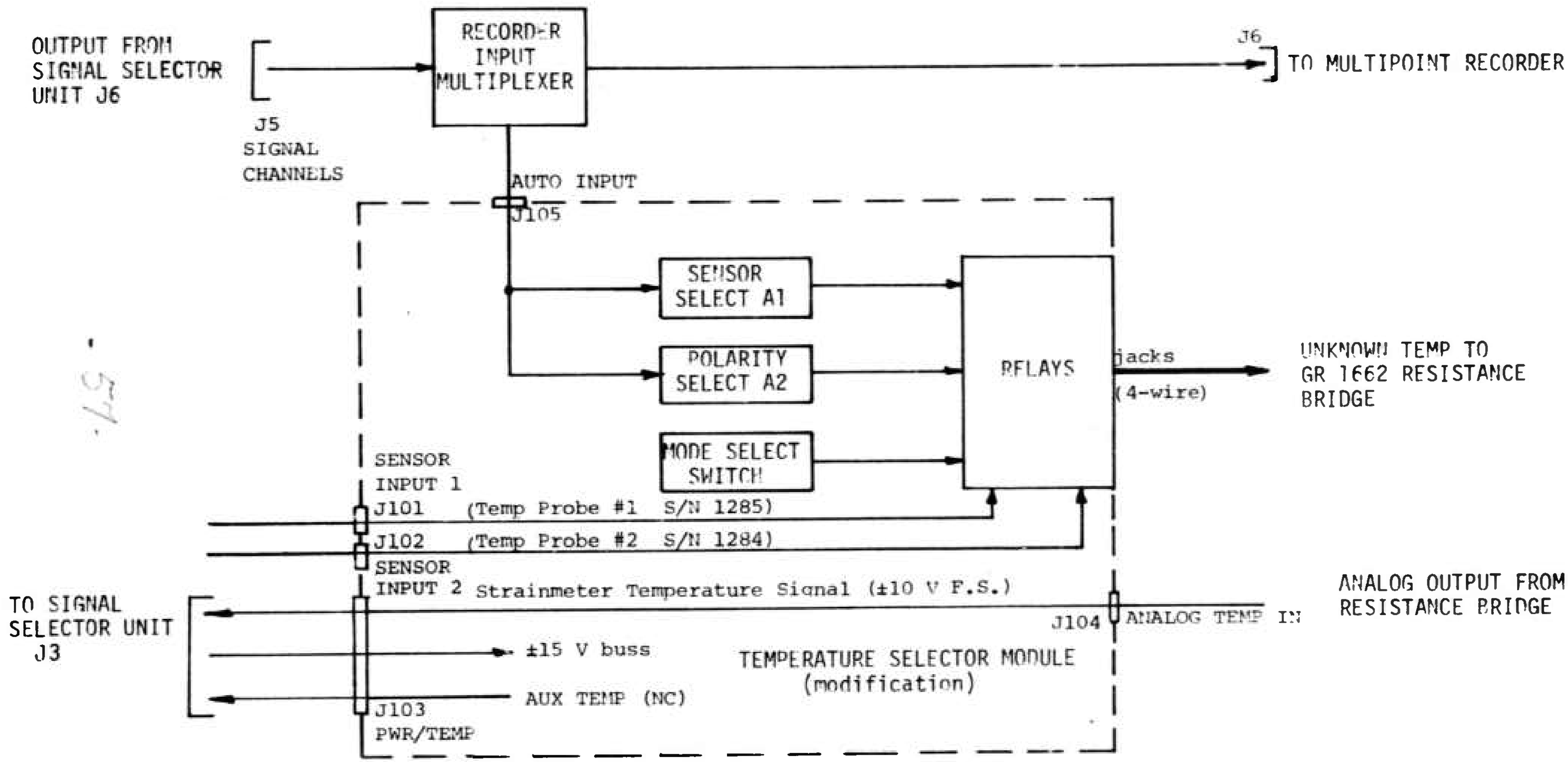

FIGURE 23

BLOCK DIAGRAM

MULTIPOINT RECORDER CHANNEL SWITCHING UNIT

automatically, padding one to match the other due to variations in nominal resistance is usually necessary to keep both on scale. The resulting output signal is cabled to the signal selector chassis where it is programmed into the recorder. Since the resistance bridge full-scale output is ±10 volts, an attenuator network is provided in the signal selector to reduce this to ±50 millivolts for recording.

TABLE 6

PROGRAMMING FOR AUTOMATIC POLARITY REVERSAL

READ Probe #2 (normal)	Recorder	Channel	20
Switch to Probe #1 (normal)	"	"	21
READ Probe #1 (normal)	"	"	2
Switch Polarity to (REV)	"	"	3
READ Probe #1 (REV)	"	"	8
Switch to Probe #2 (REV)	"	"	9
READ Probe #2 (REV)	"	"	14
Switch Polarity to (normal)	"	"	15
READ Probe #2 (normal)	"	"	20
Switch to Probe #1 (normal)	"	"	21

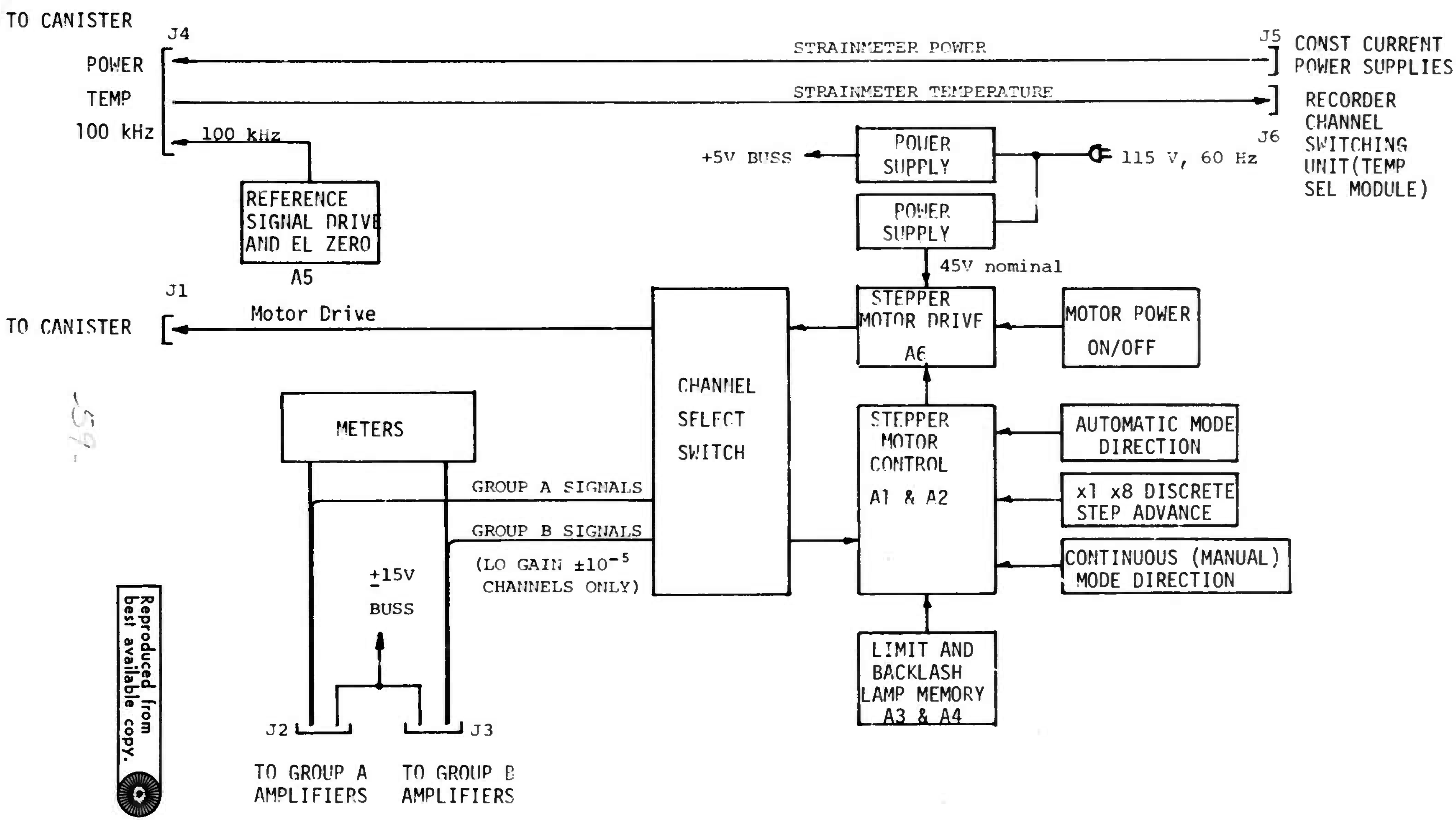

FIGURE 24

BLOCK DIAGRAM

STRAINMETER MONITOR AND CONTROL UNIT (MODEL 103327)

2.3.2.4 Strainmeter Monitor and Control Section

The principal function of this unit is to provide power and control of the stepper motors that are used to zero and calibrate each strain sensor. Logic circuitry is used to properly energize the phases of these three-wire permanent magnet motors for forward or reverse operation. The motors may be operated continuously for coarse adjustment, at a rate of 68 steps per second, or in discrete bursts of 8 steps (34 steps/second rate) or 1 step (4.25 steps/second rate), for fine adjustment. Although the motors operate at a nominal 28 volts at 0.12 ampere, an adjustable power supply is provided to compensate for line loss which is approximately 4 volts per 1000 feet with 22 Ga wire and may be larger due to drive circuit losses and transmission line capacitance. Power is manually switched off to prevent motor dissipation when stopped.

When making large changes in the sensor position, such as after emplacement where it may take 1/2 to 1 hour to drive the mechanism 0.015 to 0.030 inch to sensor null from the backed-off position, it is possible to make use of an automatic shutoff. The data amplifier signals are sensed and logic operation is inhibited when the sensor is approximately $\pm 3 \times 10^{-6}$ strain units from zero. Electrical lockouts prevent operation in any direction beyond the limits except toward zero. Further adjustment is accomplished manually with discrete bursts of pulses. After any extended operation of the motors, it is necessary to wait for the temperature to return to normal (1 hour or less typically) before making the final brief adjustment. A provision for automatically disengaging the gear train from the lead screw spur gear, i.e., backlash, was found not to be necessary.

For calibration, a manual mode is provided which disables the lockout and allows the sensor to be driven off scale in either direction. By electronically counting the steps, the sensor motion corresponding to the resulting output change can be determined for the fixed displacement per step. However, positive and negative runs are usually necessary on the high gain channels to average thermal effects. A

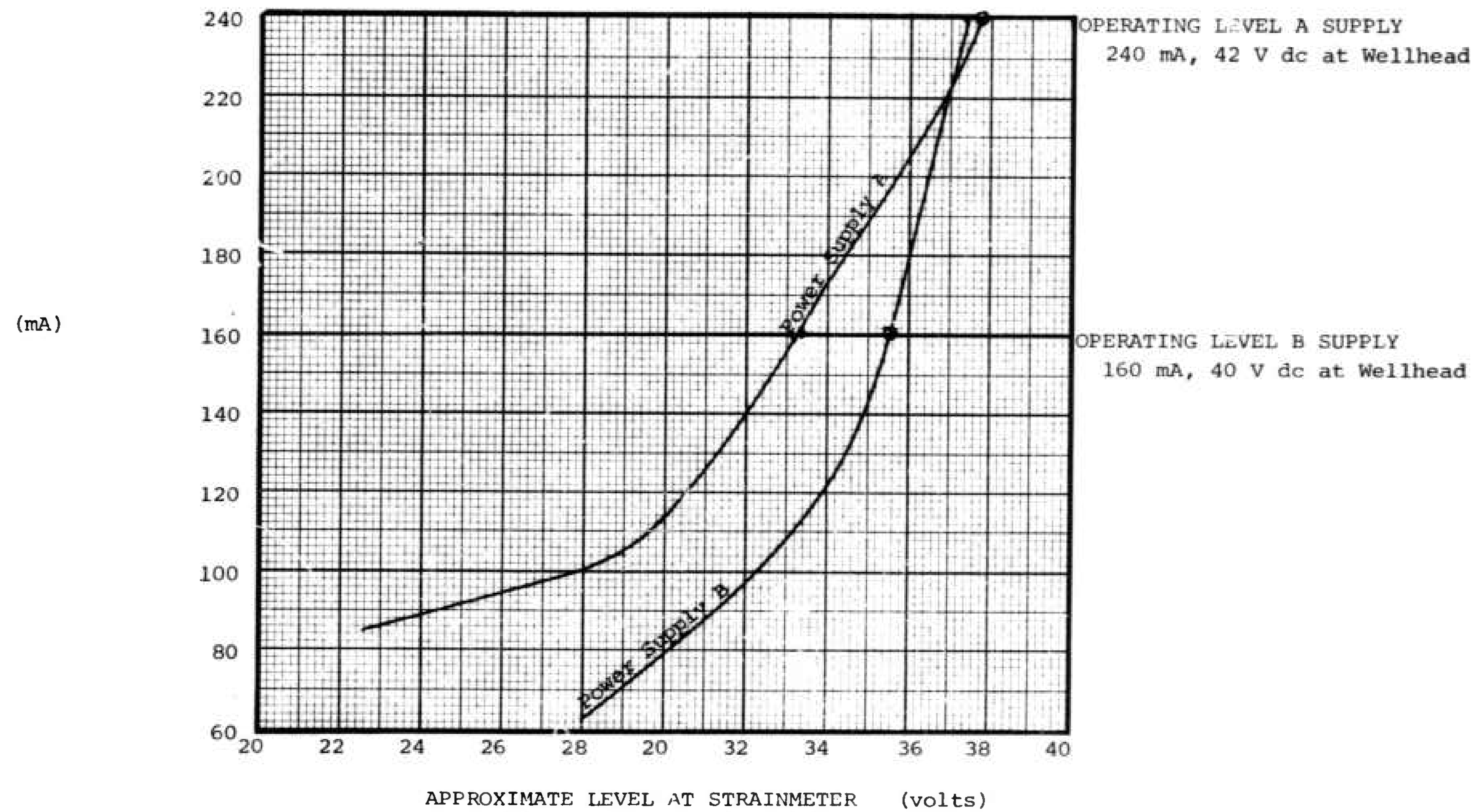

FIGURE 25

STRAINMETER POWER SUPPLY CHARACTERISTICS

short period of operation after reversing the motor prior to calibration is necessary to insure operation in a mechanically linear regime. It is extremely important to restrict motor operation in the positive direction (i.e., after passing through sensor zero) since mechanical stops will be reached after 0.004 inch or approximately 10^{-4} strain units of travel.

Other functions provided in this unit include the stable reference signal source for the strain sensors, a means of checking the downhole electronics zero offset and voltmeters to monitor the data amplifier outputs. The reference oscillator has a stability of ±0.01% over 0 to 50°C. Additional filtering and amplification is provided for driving the 100-kHz signals over long cables to the strainmeter. The electronic offset check is a -15 volt dc level multiplexed on the reference signal lines to turn off the drive amplifier downhole.

2.3.2.5 Power and Grounding

Downhole power is supplied by two HP 6177B constant current power supplies as described in Section 2.3.1.2. In the final shallow-hole system there were four sensors in Group A and two sensors in Group B. Thus, the loading on the supplies and behavior of the downhole regulator was different for the two groups. Figure 25 summarizes the characteristics and voltage levels required at the wellhead system to supply the necessary current.

Since the strainmeter canister is electrically coupled to the ground in an uncontrollable way, provisions were made for trying several grounding schemes. The final setup, Figure 26, has worked well in the shallow-hole installation and no spurious noise effects have been observed.

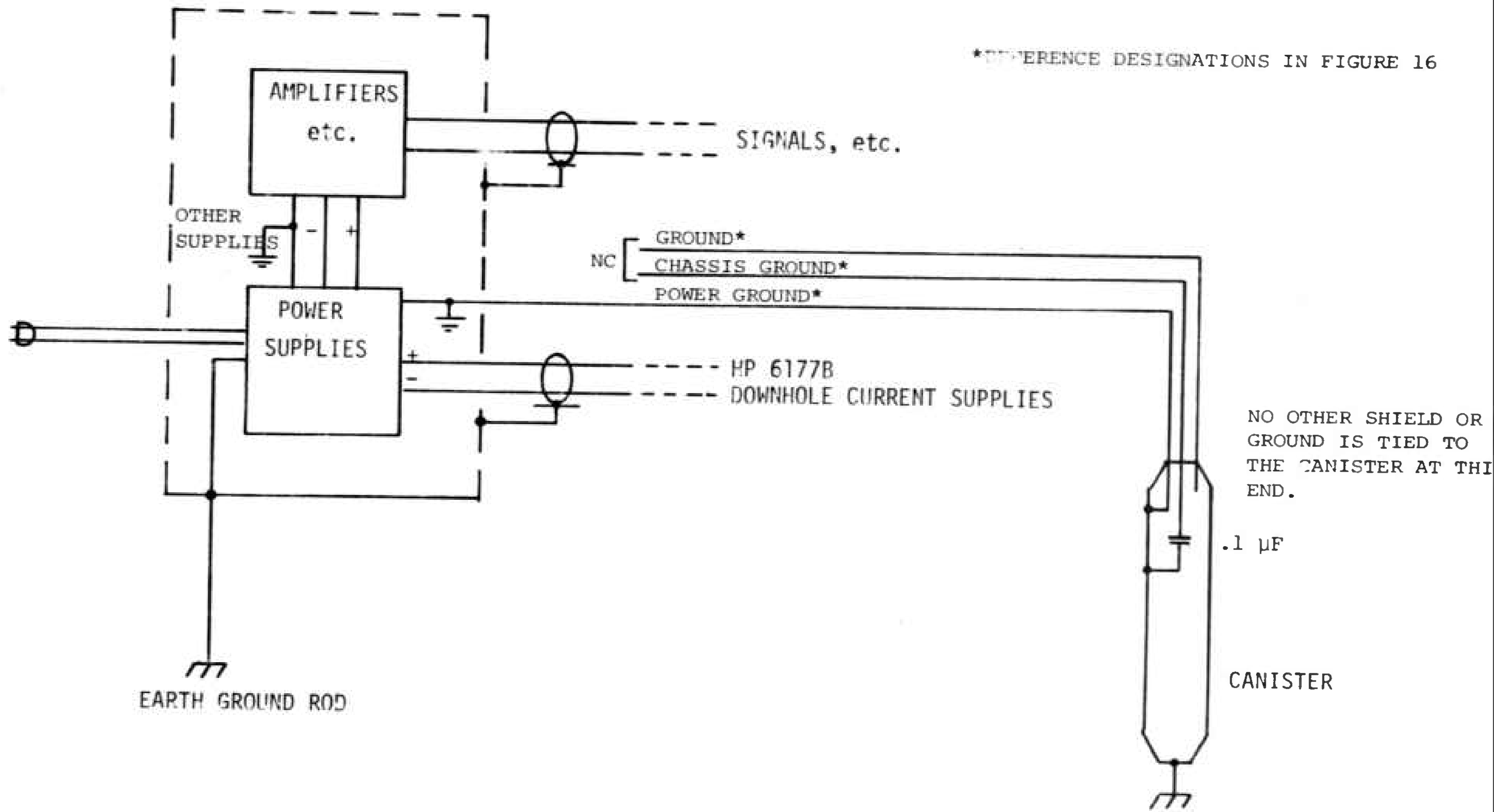

FIGURE 26
SYSTEM GROUND DIAGRAM

2.4 DOWNHOLE CABLE

The basic cable requirements were dictated by the electronic system design reliability tradeoffs, discussed in Section 2.3. These considerations resulted in a fairly large number of conductors being required in order to minimize the downhole electronics and thus maximize overall system reliability in this permanently emplaced application. In those applications where a full complement of redundant strain sensors is not required, the conductor count can be significantly reduced, thus simplifying the cable. For deep borehole applications, an armored underwater type cable must be used, regardless of the installation method, to provide protection and self-supporting capability over a significant period of time in a water-filled hole. For the shallow mine tunnel application accomplished on this program, three standard electronic signal cables (Belden #8776) were used, consisting of multiple sets of 22-gauge, twisted, shielded-pair conductors in an unarmored vinyl jacket.

The cable design chosen for deep-hole applications consists of 100 insulated 22-gauge and 5 bare 24-gauge stranded copper conductors. The relatively high number of conductors, significantly in excess of the 72 maximum required for up to eight sensors, results from the packing required to meet cable diameter constraints. All conductors are cabled in five concentric layers with electrostatic mylar foil shields in contact with the bare drain wires between layers. Conductor assignments are chosen to segregate the various functions and place the most sensitive signals at the cable interior. Table 7 illustrates a possible configuration. The cable is designed for high-pressure underwater applications and has a polyethylene jacket applied over the cabled conductors. Price quotes for this cable, or near equivalent, range from 4 to 6 dollars per foot depending on the total length and specific design features.

For normal applications the cable would be armored with two helically applied layers of galvanized approved plow steel wire for protection and loadbearing capability. This arrangement is nominally torque balanced for all anticipated loads to prevent twisting and kinking and can provide a cable breaking strength in excess of 60,000 pounds. The cable payload

should be restricted to a working maximum of 10,000 pounds to insure against conductor damage in the event of jamming or pull tests. In intermediate depth applications, the cable need only support a payload of approximately 1000 pounds consisting of the canister and sinker plus the weight of the cable (approximately 1.5 pounds per foot) which would result in a total load of 4,000 pounds in a 2,000-foot emplacement. In very deep installations where the grout pipe is the principal load bearing member the cable need nominally support only its own weight and a small tension load to prevent kinking. However, it may be desirable to consider having the cable provide backup capacity for supporting the entire instrument train in the event of pipe slippage, in which case the grout pipe weight of approximately 3 pounds per foot must also be considered. After the grouting operation is complete, the cable could be slacked off so that it need only support its own weight. Depending on specific borehole conditions, armor corrosion protection may be needed at the water line.

The downhole end of the cable would be terminated with an underwater connector of the type that will provide a blocked interface which is necessary to prevent loss of the instrument fluid into the cable. Possible configurations are shown in the figures in Section 2.6. For intermediate depth applications, both the electrical and mechanical termination can be provided in a single standard metal shell connector such as the Brantner and Associates, Inc. Model MSS-Q-85-CCP connector which contains 85 16-gauge contacts molded in a fiberglass-filled epoxy insert. The connector is molded to the polyethylene cable jacket and the armor is terminated in a load-bearing assembly mated to the metal shell of the electrical connector. For very deep installations, it is necessary to break out the end of the cable into three separate pigtails due to the dimensional constraints imposed by the grout pipe. These would be molded directly to O-ring sealed 32-pin fiberglass inserts, without an outer shell, to plug directly into the annular space of the top end of the canister and be held in place with a clamp. A special armor termination unit would be anchored to the grout pipe above the breakout, thus avoiding strain on the connectors. The wellhead or surface end of the cable can be terminated with a conventional environmentally resistant connector.

While this cable is much larger than is commonly used in borehole applications, it is definitely within the state of the art. Consultation with manufacturers, designers, and installers of borehole cable has indicated that construction and deployment could be achieved without major difficulty. The cable design is rated for operation at temperatures greater than +50°C for a minimum of one to two years in a water-filled borehole. However, the basic design may be realized using high performance materials for installations of up to 10,000 feet of depth, operating temperatures of up to 125°C, and corrosive environments. Pressure testing of the bulk cable is not necessary but a one-time 10,000 pound load test and electrical tests should be performed during the cable manufacturing process with additional detailed inspection and tests done before and after the termination operation. The finished cable should be wound under 1500 to 2000 pound tension and shipped on a steel drum from which it would be payed out during insrallation.

TABLE 7

TYPICAL DEEP BOREHOLE CABLE CONDUCTOR ASSIGNMENTS

LAYER	FUNCTION	SIGNAL	SPARES	TOTAL	DRAIN
1	Spare	-	8	8	1
2	Temperature (2 of 4 each)	8	6	14	1
3	DC Power (2 of 4 each) and Drive Signal (2 of 2 each)	12	8	20	1
4	Sensor Output (8 of 2 signal and 1 common each)	24	2	26	1
5	Sensor Motor Control (8 of 2 each) and Pressure Equalizer Solenoids (2 of 2 each)	28	4	32	1
	TOTAL	72	28	100	5

2.5 INSTRUMENT GROUT

In order to insure that the sensors will exhibit the same elongation in each axis as the rock, a positive method of coupling the canister to the borehole walls is required. Experience indicates that mechanically expanding jacks will produce high stress points which will creep, destroying long-term calibration. Therefore, the more reliable technique of grouting the canister in place was chosen. A minimum annular grout thickness of approximately 1/2" is used to minimize the effect of dimensional change during curing and allow room for the grout to flow up past the canister. Fins and centralizers are placed above and below the canister to insure that the package is centered and that the grout will flow all around it. The borehole must be thoroughly flushed since pockets of drill mud will not only impair adhesion of the grout to the walls but will create serious distortions in the transmitted strain field.

In order to achieve controlled and reproducible results, a special grout was developed by the US Army Engineers, Waterways Experiment Station, Vicksburg, Mississippi, with characteristics as summarized in Table 8. The grout is basically a portland cement which has been modified to produce a positive expansion of approximately 1 part per thousand during curing so that it will not break away from the canister or the hole wall, but is small enough so that it will not damage the sensors. In addition, a fly ash is used to control the exothermic cure temperature rise which was less than 2°C in the shallow hole installation and should be less than 1C to 15°C in deep installations where large volumes of grout are involved. Retardants are used to maximize the working time which tests show could be as little as 2-1/2 hours in a 100°F environment, although as much as 4 to 8 hours can be achieved in cooler environments or by chilling the grout. This grout, which is a medium viscosity slurry, is highly pumpable although considerable expertise is required to handle it properly. The instrument grout would be used in the immediate vicinity of the strainmeter only and staging grout to the surface, if used, can be anything including Betenite which is cheap and drillable.

TABLE 8

DEV-4 GROUT CHARACTERISTICS

	DESIGN GOALS	ACTUAL RESULTS
STABILITY	$<10^{-8}$/day after 60 days	1.1×10^{-7}/day after 360 days
INITIAL EXPANSION	100 - 500 ppm	1000 ppm
TEMPERATURE COEFFICIENT	≃ +10 ppm/°C	≃ 5 ppm/°F (est)
SHEAR BOND STRENGTH (at 28 days)	100 - 200 psi	605 psi (sand blast) 725 psi (grooved)
COMPRESSION STRENGTH (unconfined)	2000 psi	3980 psi
TENSILE BOND STRENGTH	10-20 psi	-
BULK MODULUS	$2\text{-}3 \times 10^{6}$ psi	-
DENSITY	≃100 lbs/ft³	110 lbs/ft³
VISCOSITY	A slurry	A slurry
TEMPERATURE RISE @ CURE	<25°C	<10°C (est)
WORKING TIME	4 to 8 hours	2-1/2 hours minimum at 100°F

A comparison of the design goals and actual results of the key properties for the grout formulation designated DEV-4 are shown above. Tests indicated that the bonding strength to the bare stainless steel canister surface, initial expansion, exotherm and handling properties are all entirely satisfactory for the application. Hydrostatic pressure does not have any significant effect on the cured properties of the grout (see Appendix B).

The time required for the grout to stabilize is considerably longer than desired presumably due to the tradeoffs made to achieve the desired expansion and working time. Even though the development tests indicated the grout cured to a stability of approximately 10^{-7}/day after one year, which represents a strainmeter stability of 1.6×10^{-8}/day if the grout thickness is 1/2 inch compared to a canister radius of approximately 3 inches, actual results with the shallow-hole installation indicated stabilities on this order were achieved after 200 days and are continuing to improve. Usable tidal data was obtained after about 60 days and it is possible secular strain information could be obtained after 4 to 6 months by utilizing suitable computer techniques to compare the output of all sensor components.

2.6 INSTALLATION METHODS

A significant part of the design task was devoted to defining requirements for future deephole strainmeter installations in cooperation with consultants, experienced in borehole instrument fielding, from the Corps of Engineers and Sandia Laboratories. Although the strainmeter design has been ruggedized to the extent possible, it is still ralatively fragile for this type of operation and particular care must be taken with all facets of the installation operation to ensure a successful emplacement. Specific emphasis should be given to the control of borehole characteristics as well as preparation, and lowering of the instrument train and grout preparation. Significant savings in installation and instrument assembly costs can be achieved by using different installation techniques for intermediate depth boreholes on the order of 2000 feet or less.

The installation of the strainmeter in a borehole that is at least cased to the level of competent rock is necessary to significantly reduce risk in a number of operations. Rock falls during installation in an uncased hole are highly probable and can easily result in damage to the thin-wall canister or inhibit the proper flow of grout. In addition, the flushing operation which is critical to the success of the grouting can only be checked by observing the flow at the top and this usually requires casing. A casing with a minimum ID of 8-5/8 inches and capped with an 18-inch high nipple is recommended. If it is ever necessary to use an uncased hole, then a protective shroud should be considered even though it is an undesirable addition to mechanical complexity. It it recommended that the maximum curvature of the borehole axis should be no more than 2 degrees per thousand feet to avoid placing undue bending stress on the instrument canister.

The borehole should terminate in a nominally 7-7/8 inch diameter cored section of competent rock that is 40 to 60 feet deep or twice that if a follow-up installation is planned. The cored hole must be fairly well centered in the borehole and step chamfered in order to insure satisfactory entry of the instrument equipment and minimize bending. It is desirable that the borehole be within 5 degrees of vertical at the in-

stallation depth so orientation will not be a factor in the strain measurements. Complete geological (including electrical and sonic), caliper, direction and temperature logs from surface to depth are advisable to aid in planning the installation and interpretation of data. Control of instrument orientation is not considered necessary since it can be computed from the multicomponent data.

Just prior to installation, the cored section of the borehole should be thoroughly cleaned by scrubbing and flushing to insure an adequate bond of grout to the tock. Also a mandrel or dummy canister, that is approximately 10% longer than the actual instrument, should be lowered in the borehole to serve as a fit check and insure safe passage of the actual instrument. The mandrel could be painted and contain simple displacement gauges to serve as a rough check of the conditions that were encountered during the descent. Although this operation would take from 12 to 14 hours, in a typical 5000-foot installation using grout pipe, it is considered to be well worth the effort.

Proper field installation of the controlled expansion grout requires a high degree of quality control. The annular gap between the canister and hole must be 1/2 inch minimum and free of irregularities. All equipment used in the preparation and the installation of the grout must be extremely clean. Although the grout mixture contains retardants to provide adequate working time, mixing at low temperatures and further chilling may be required if elevated temperatures are expected during the preparation and installation to insure that a four-hour-minimum hold time is achieved. The volume of grout is relatively small which will be an advantage in controlling the preparation, but is still sufficiently large that commercial equipment will be required for mixing and especially for handling the pressures involved in very deep installations. Supervision of the grouting operation by qualified personnel is required to insure the quality of the operation.

To accomplish very deep installations, the canister must have an integral section of grout pipe in its center since the grout must be pumped in below the canister and forced up the annulus around it in order to insure

complete bonding of the canister in the borehole. This approach requires the instrument canister to be rigged up as shown in Figure 27, where the grout pipe is the principal load-bearing member for the descent into the borehole, the downhole cable is attached to the sections of grout pipe permanently connected to the instrument canister and the perforated section of grout pipe is connected to the bottom of the canister. A grout pipe such as Hydril CS tubing with a 1-1/2 inch diameter fabricated from N80 alloy (yield strength of 64,000 pounds) is adequate since the grout is in slurry form. Although the cable will not have to carry the weight of the instrument train, it should be armored for protection from abrasion and shock loads as well as to be self-supporting in a free-hanging state after the grout pipe is removed. The downhole cable, which must be nominally torque balanced, will be payed out from a separate winch with a continuous monitor of cable load so that a known tension can be maintained on the cable to prevent its wrapping up on the pipe and to prevent the danger of breakage due to the cable taking too much of the load. When the instrument package is in the cored hole, as determined by depth and weight indications, the system will be energized and each sensor centered and calibrated prior to grouting. In order to insure thorough grouting it will be necessary to use a reasonably large volume of grout installed at high velocity (which would tend to scour the residual mud) sufficient to cover the canister to depths of 20 to 30 feet. The backoff sub, which is a joint with a left-hand thread, would be located approximately 60 feet above the canister in order to anchor the pressure equalizer vent tube opening at a safe distance above the grout level. A wiper could be pushed down the grout pipe to insure all the grout gets down the hole, although a probable error of ten feet in depth is predicted in any case. The retardants in the grout can provide a hold time in excess of four hours during which sensor operation can be checked and provisions made to flush out the grout or pull the instrument train if there are indications of serious trouble.

For installations involving depths of 2000 feet or less, it is possible to eliminate the grout pipe through the instrument package, thus considerably simplifying the instrument assembly, and installation, by preinstalling the grout in the borehole and then sinking the instrument package into the still fluid grout of medium viscosity as illustrated in Figure 28. In this

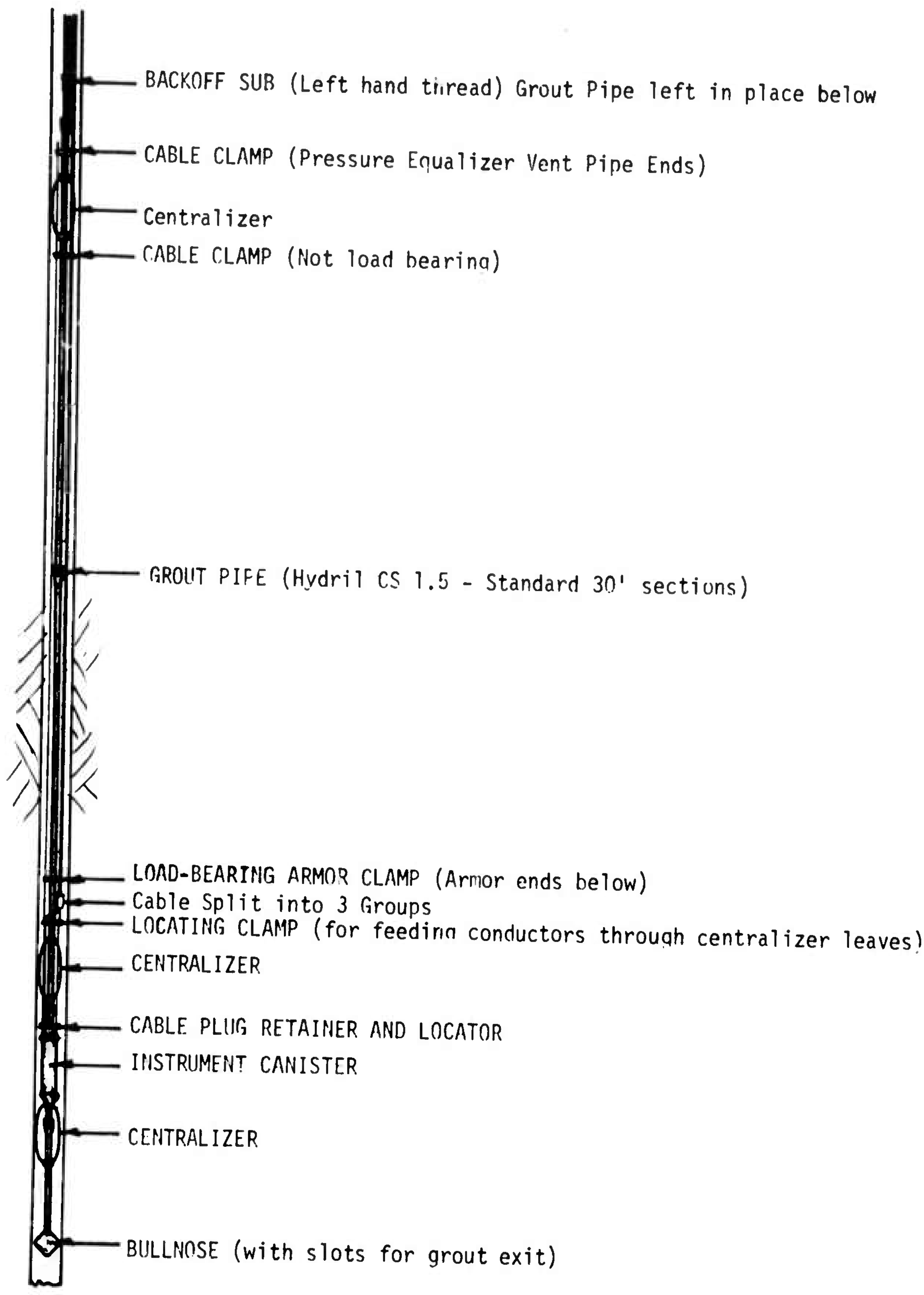

FIGURE 27

DEEP BOREHOLE INSTALLATION

arrangement, the entire instrument load is borne by the nominally torque balanced instrument cable which is electrically and mechanically terminated in a single connector at the canister interface. The basic borehole preparation and cleaning requirements remain as described above; however, the borehole must be bailed dry prior to the grouting operation to prevent separation or dilution of the grout mixture. The grout installation is accomplished by lowering a dump bailer to the bottom of the cored instrument hole. Two trips with a 20 to 30-foot bailer would be required which can be accomplished in less than 1 hour for a 2000-foot borehole. It will take approximately 1 hour to carefully lower the instrument package into the dry hole assuming the instrument train was prepared in parallel with the grouting installation. Since it is estimated that a grout working time of four hours can be achieved with the use of retardants and by chilling, there will be a minimum of two hours for preliminary checkout before there is even a possibility of the grout initial set occurring. The borehole will be refilled with water after the grout has set.

Cable handling techniques are basically the same regardless of which installation approach is used. A powered steel drum type winch with adequate braking capacity is recommended for use on the installation operation. Level winding and large sheaves to minimize the amount of cable curvature is essential in paying out the cable to prevent conductor breakage. Also, a line scale should be used to maintain a correct cable tension and prevent damage. Approximately 300 feet of cable would be allocated for surface handling requirements including a minimum of three final turns of the drum. After installation is complete, a tee clamp could be used to anchor the cable to the wellhead and the armor would be grounded to the borehole casing for electrical protection.

Completion of the installation will depend on the specific environment. In some instances, stage grouting to the surface with an inexpensive material, such as Betenite, may be desirable. In others, allowing water to stand in the casing or perforating the casing to couple the ground water may be preferable. The decision is primarily determined by the expected hydrostatic pressure effects since the 20 to 30 feet of grout over the instrument are sufficient to attenuate temperature effects in the borehole fluid.

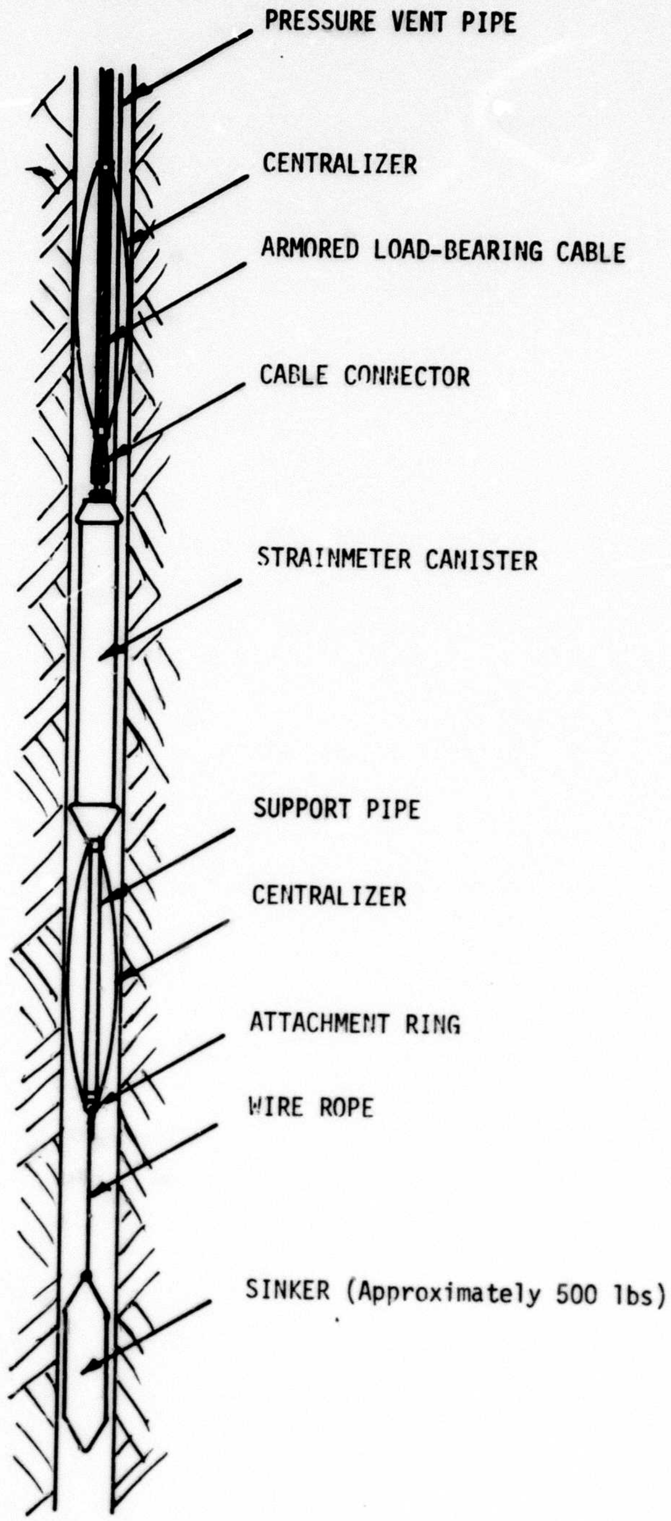

FIGURE 28

INTERMEDIATE DEPTH INSTALLATION

3. SHALLOW HOLE INSTALLATION

In order to evaluate the borehole strainmeter design performance at a significant depth below the surface without undue complexity, a shallow-hole version was constructed for installation in a mine tunnel. To facilitate handling, the canister was made shorter by deleting the pressure equalizer equipment and the pressure vessels for the electronics. These items were not required since there is no standing water although the instrument fluid is coupled to the tunnel atmosphere. Since there was little risk of mechanical damage during installation and to further reduce size, only one extra sensor of each type was included, for a total of four horizontal and two vertical components, to provide measurement redundancy.

The installation site, the Black Butte Mine, near Mina, Nevada, also contains University of Nevada long-baseline strainmeters. The abandoned mine tunnel, Figure 29, is situated 700 feet horizontally into a mountainside near the Garfield Hills active seismic area. The borehole strainmeter is located approximately two-thirds of the way between the University of Nevada's first and second long-baseline strainmeters. The vertical distance from the borehole installation to the surface of the mountainside is approximately 300 feet which provides a reasonable attenuation of surface effects. In addition, bulkhead baffles in the tunnel aid in providing the good thermal stability required for proper instrument performance. The tunnel air temperature is approximately 16°C with an estimated stability of 5 to 10 m°C short term (somewhat more long term) and will vary somewhat less at the strainmeter installation depth. It is expected, however, that considerably more stable conditions can be achieved in deep boreholes. Humidity is high with condensation but no standing water at the instrument location.

Site preparation and installation of the strainmeter was completed on 1 December 1973. The drilling of the shallow boreholes was done by personnel from the US Army Corps of Engineers, Foundation and Materials Branch, Mobile, Alabama. The grouting of the strainmeter canister in the borehole was performed by personnel from the US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. The strainmeter is installed in a 5-3/4 foot deep hole in the hard rock floor of the tunnel

which is an altered rhyolite. While the rock is basically competent, there were several large fractures intersecting the borehole. The borehole diameter is nominally 7-3/4 inches but nonuniformities resulted in a grout annulus ranging from 1/2 to 1 inch around the 6-1/2 inch strainmeter canister. There were no logs taken of the hole, but core samples were obtained and are available. The geometric center of the sensor array is located approximately 41 inches from the hard rock floor. There is approximately 18 inches of rubble on the tunnel floor over the hard rock layer which provides some additional insulation. An insulated box has been placed over the borehole in which several turns of the electrical cable have been placed to attenuate thremal conduction effects.

Prior to the grouting, the strainmeter canister was cleaned and installed in the hole so that the redundant horizontal sensors designated H3A and H3B are oriented North 17.4° East, i.e., they are approximately parallel to the University of Nevada strainmeter component that is oriented North 23° East. Orientation of the remaining strainmeter components is given in Figure 29. A thorough electrical checkout was performed prior to installing the grout. Each sensor was then disengaged approximately 0.007 inch to compensate for the expected grout expansion during installation and curing. The Waterways Experiment Station grout formulation, designated DEV-4, was poured in two stages and thoroughly worked to ensure that the can grooves were filled. The grout exotherm resulted in a temperature rise of 1-3/4°C during the first 24 hours (approximately) which is consistent with the published grout test data.

On the second day after grouting, one vertical and one horizontal sensor were run on scale to check the strain rate and general operation. Only two sensors were checked to minimize thermal perturbations, but the operational indications of the other sensors appeared normal. The drift rates, after thermal conditions had stabilized, were approximately 20 parts per million per day for the horizontal sensor and four parts per million per day for the vertical sensor. These figures are in rough agreement with the Waterways Experiment Station data which indicated a strain rate of 50 parts per million per day can be expected at this stage of the cure.

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APPROXIMATE TUNNEL LAYOUT

BLACK BUTTE MINE, Section 26 MINA, NV Quad

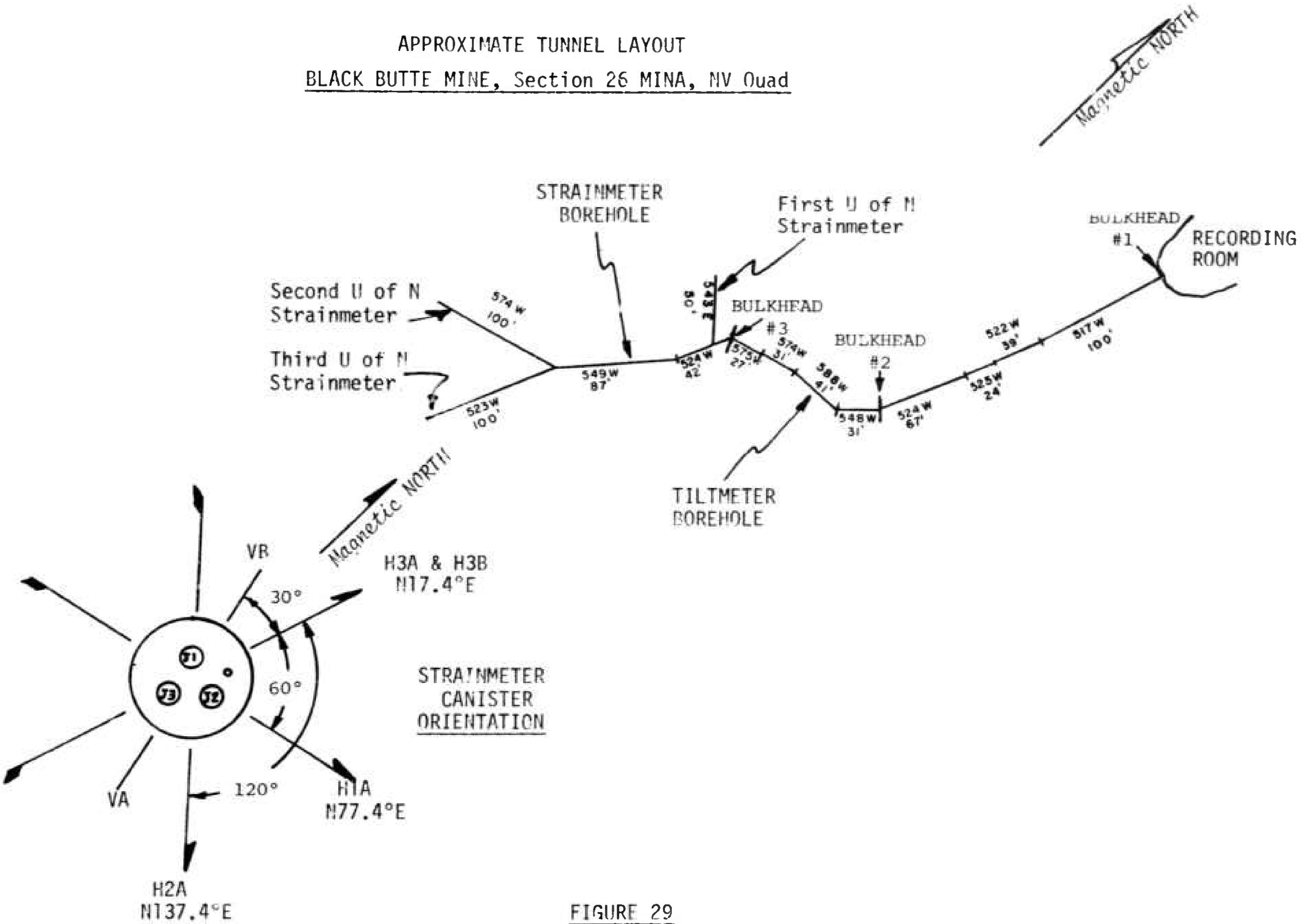

FIGURE 29

11

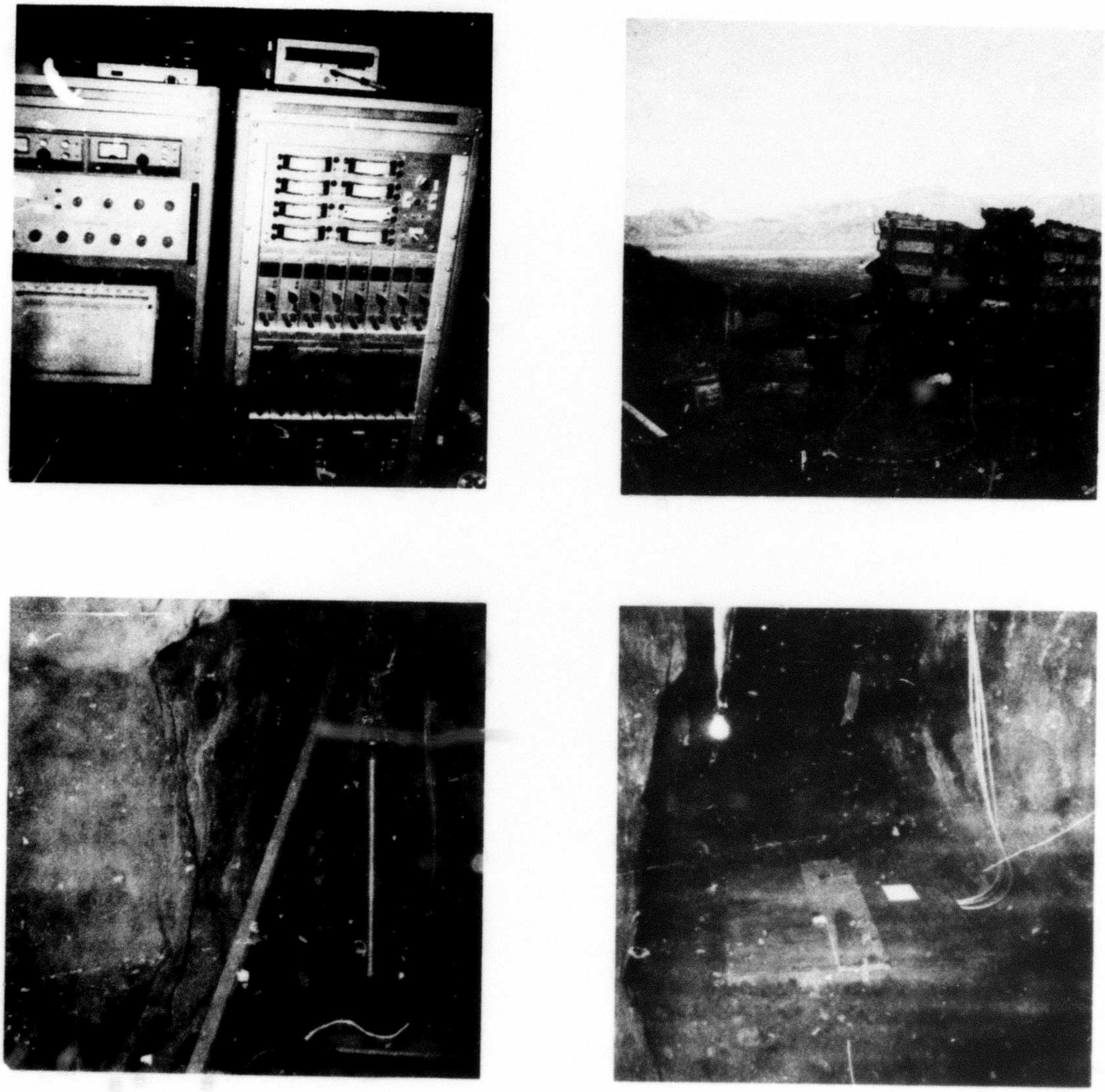

FIGURE 30

STRAINMETER INSTALLATION PHOTOS

These two sensors were then calibrated with normal results and backed off from 0.003 to 0.005 in since the amount of additional dimensional adjustment that would be experienced was unknown. All sensors were thus left in an offscale state since it took several weeks before grout stability was suitable for long-term recording. However, the strainmeter canister power was left on so thermal stability would be reached prior to the start of recording operations.

All sensors were run on scale and long-term recording operations started on December 20. An initial calibration of the sensors was performed and verified proper operation of all channels. Numerical results were only obtained for the low gain channels, due to time limitations, since the high gain channels are fixed at an approximate ratio of 10. The calibration data for the instrinsic sensor response shown in Table 9 is estimated to have an overall accuracy of better than 20% as judged from previous results. Subsequently scheduled detailed calibrations were not performed to avoid perturbing the strainmeter operation while attempting to obtain a significant continuous record required to analyze earth tides and estimate strainmeter stability.

The calibration figures do not include compensation for borehole or canister, grout and rock modulus effects which require complex theoretical analysis and detailed comparison with actual data to be meaningful. It is estimated that these factors can result in an enhancement of strain ranging from 50 to 150% transverse to the borehole and an attenuation of strain of up to 50% parallel to the borehole. Since the effects are fixed and relatively small, a detailed understanding of these factors was not considered necessary for the initial evaluation of instrument performance but should be evaluated for future installations. Further, the recorded tidal amplitudes were of the same order as those recorded by the University of Nevada long-baseline strainmeters.

The effects of grout stabilization, Figure 31, improved at a rate roughly in agreement with the Waterways Experiment Station development data. By late February it was possible to increase the recording sensitivities on some channels sufficiently to observe earth tide data. The spread in rates from sensor to sensor and the fluctuation with time are thought to

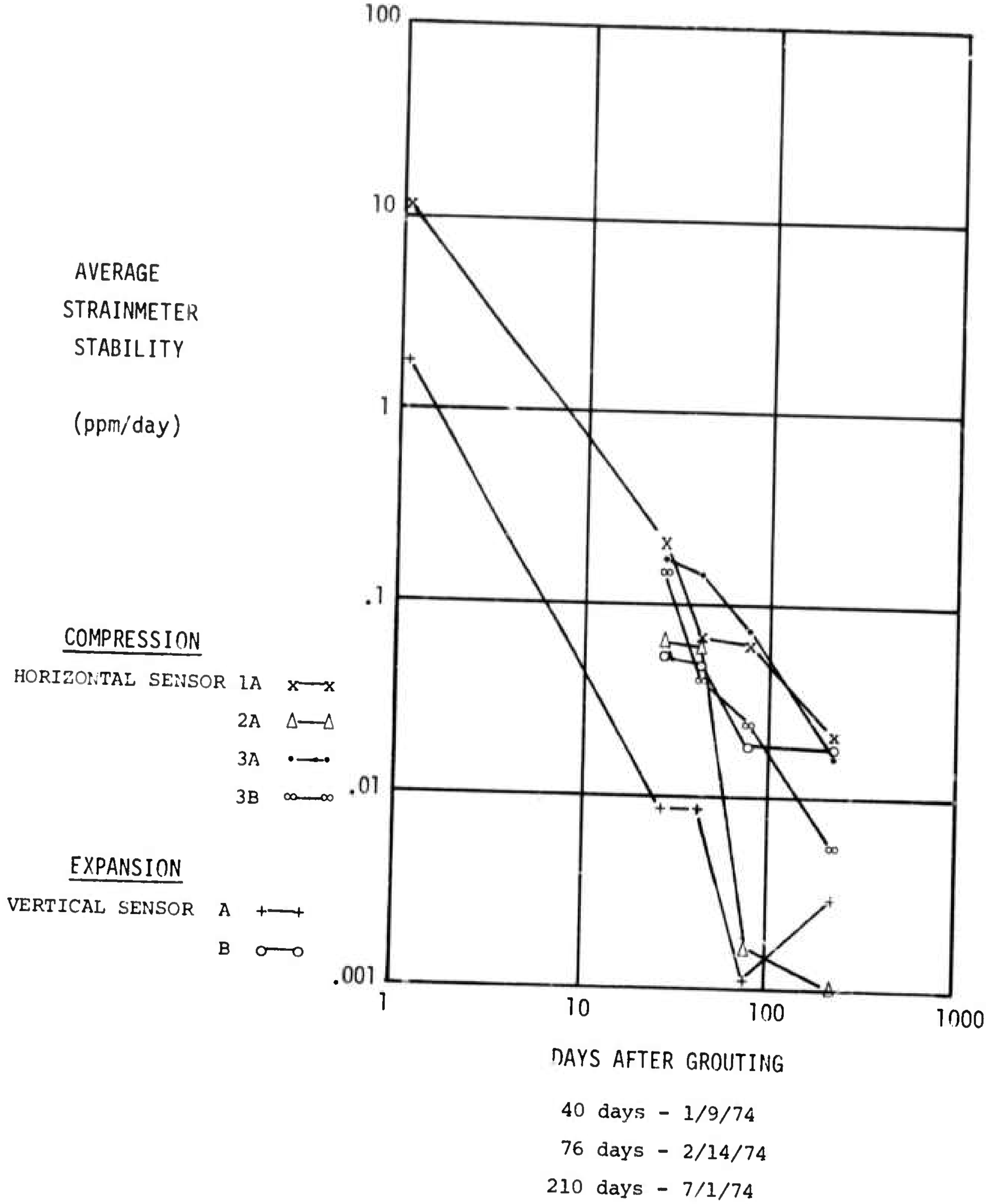

FIGURE 31

BOREHOLE STRAINMETER STABILITY AFTER INSTALLATION

TABLE 9

PRELIMINARY STRAINMETER CALIBRATION
(Strain Units)

SENSOR	STRAIN CHANNEL	CHANNEL SATURATION	RECORDER SPAN SETTING						
			20 SPAN	10 SPAN	5 SPAN	2 SPAN	1 SPAN	0.5 SPAN	0.2 SPAN
H1A	LO GAIN ($x10^{-6}$) HI GAIN ($x10^{-7}$)	42.4	28.28	14.14	7.07	2.828	1.414	0.707	0.2828
H2A	LO GAIN ($x10^{-6}$) HI GAIN ($x10^{-7}$)	48.4	32.25	16.13	8.06	3.225	1.613	0.806	0.3225
H3A	LO GAIN ($x10^{-6}$) HI GAIN ($x10^{-7}$)	32.3	21.55	10.78	5.39	2.155	1.078	0.539	0.2155
VA	LO GAIN ($x10^{-6}$) HI GAIN ($x10^{-7}$)	23.5	15.68	7.84	3.92	1.568	0.784	0.392	0.1568
H3B	LO GAIN ($x10^{-6}$) HI GAIN ($x10^{-7}$)	25.1	16.74	8.37	4.19	1.674	0.837	0.419	0.1674
VB	LO GAIN ($x10^{-6}$) HI GAIN ($x10^{-7}$)	20.6	13.69	6.85	3.43	1.369	0.685	0.343	0.1369

NOTES:

1. Calibration data is for the sensor only and is based on a 6-1/2"horizontal baseline and a 10-inch vertical baseline. The data is not compensated for canister thickness or borehole geometry effects. For the purpose of the preliminary analysis these effects are estimated to be small enough (<10) so the measured earth tide amplitudes are in the right order of magnitude.
2. The span value refers to the recorder amplifier setting that produces the indicated full-scale recording sensitivity which is equivalent to a ±5V signal, i.e., a 10-volt signal swing.
3. Channel saturation refers to the full-scale sensor deflection which saturates the canister electronics.

be due to the nonuniformity of the grout thickness and the complex situation caused by rock fractures. Although the ultimate level cannot yet be predicted, there has been continuous improvement and the strainmeter drift rates are on the order of 10^{-9} to 2×10^{-8} per day after 210 days. Problems in data analysis were also caused by frequent power failures during this time period; however, it is important to note that even though the data often went off scale and the thermal transierts lasted for hours, no permanent data offsets were observed.

Even though it has only been possible to thoroughly analyze a relatively small amount of data to date, due to the power problems and the predicted slowness of the grout curing, the instrument is clearly approaching its design capacity and no fundamental limitations have as yet been observed.

4. ANALYSIS OF BOREHOLE STRAINMETER DATA

An obvious feature which can be observed on a strain record of appropriate sensitivity is the solid earth tides; that is, the response of the yielding earth to the tidal producing forces of the moon and the sun. The amount of strain yielding is specified with one of the Love numbers, h, and Shida's number, ℓ.*

h is the ratio of the height of the tide in a yielding earth to the height of the equilibrium tide and is therefore a measure of the amount of radial displacement of a yielding planet.

ℓ relates the horizontal tidal displacement to the deforming tidal potential. If the earth would not yield, $h = \ell = 0$.

However, it is well known that any observed tidal strains are not only the result of the yielding of the earth produced by the moon and sun, but also include a superposed effect, the yielding of the earth produced by the varying surface load caused by the ocean tide. The ocean loading effect diminishes inward from the coast line, but is still believed to contribute as much as 25% of the observed strain tide in Nevada**.

The continuous recording of earth tidal strains demonstrates the presence of certain constant components of frequency. Tidal strain data are most commonly examined in terms of harmonic analyses. Many components are revealed in such an analysis because the detailed orbital relations between the earth, moon and sun are complicated.

First, there are two main semi-diurnal components. M_2 is the main lunar semi-diurnal constituent with a period of 12.421 hours. This corresponds to the tide that would be generated by an imaginary moon describing a circular orbit in the plane of the equator and traveling with the mean velocity of the real moon. Similarly we have the solar constituent S_2 with a periodicity of 12.00 hours corresponding to a mean solar half day.

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* See reference on page 4 of this report.

** Priestly, "Crustal Strain Measurements in Nevada", Bull Seismological Soc of Amer, V 64, No 4, pp 1319-1328, 1974.

In addition to the semi-diurnal components there are diurnal components. O_1 and P_1 are the main diurnal lunar and solar declinational components, with periods of 25.819 hours and 24.066 hours.

In order to resolve the semi-diurnal and the diurnal components on a strain record, a full 29-day series of tidal strain data are required. Unfortunately, because of recording limitations, strain offsets produced by the curing of the grout and lapses in the data caused by numerous power failures, we have not recorded an uninterrupted 29-day period so we will restrict our analysis to a direct comparison of segments of the observed and theoretical tides.

Theoretical tidal strains in the direction α were computed from the relation

$$E_\alpha = E_{\theta\theta}\cos^2\alpha + E_{\lambda\lambda}\sin^2\alpha + E_{\theta\lambda}\cos\alpha\,\sin\alpha$$

where $E_{\theta\theta}$, $E_{\lambda\lambda}$ and $E_{\theta\lambda}$ are the latitudinal, meridional and shear strains due to the tide generating potential of order 2, W_2

$$E_{\theta\theta} = \frac{1}{rg}\left[hW_2 + \ell\frac{\partial^2 W_2}{\partial\theta^2}\right]$$

$$E_{\lambda\lambda} = \frac{1}{rg}\left[hW_2 + \ell\left(\tan\theta\frac{\partial W_2}{\partial\theta} + \frac{1}{\cos^2\theta}\frac{\partial^2 W_2}{\partial\lambda^2}\right)\right]$$

$$E_{\theta\lambda} = \frac{\ell}{rg\cos\theta}\left[2\frac{\partial^2 W_2}{\partial\theta\partial\lambda} + \tan\theta\frac{\partial W_2}{\partial\lambda}\right]$$

Note that the relative amplitudes of the various strain components are determined by factors involving h and ℓ only.

For computation of the theoretical tidal strains we have taken as values of the tidal elastic constants $h = 0.34$ and $\ell = 0.028$. Values of h and ℓ can be determined by obtaining the best agreement between observation and theory. For purposes of our analysis, however, and in view of the fact

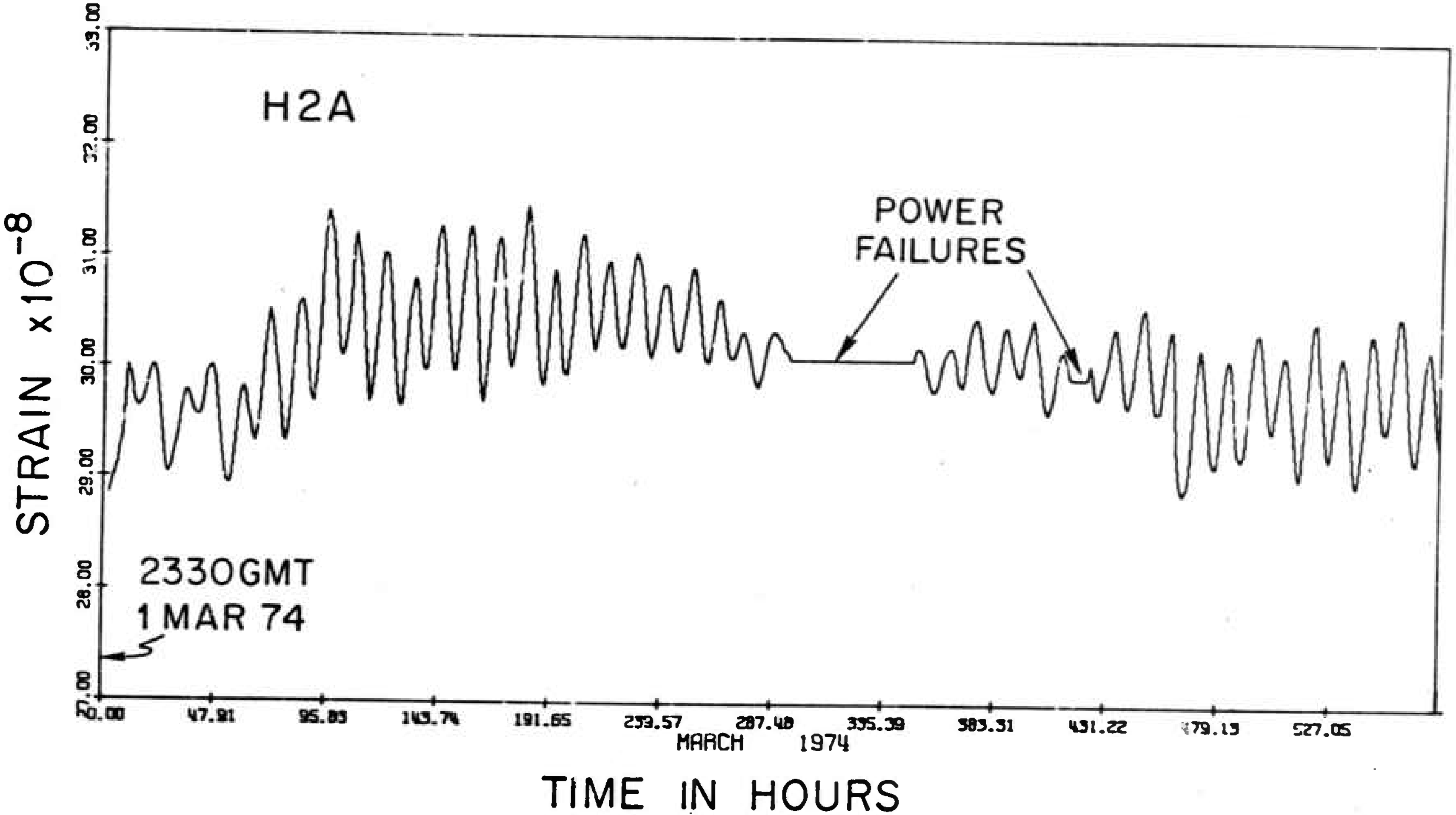

H2A
POWER
FAILURES
2330GMT
1 MAR 74
STRAIN x10^{-8}
27.00
28.00
29.00
30.00
31.00
32.00
33.00
0.00
47.91
95.83
143.74
191.65
239.57
287.48
335.39
383.31
431.22
479.13
527.05
MARCH 1974
TIME IN HOURS

FIGURE 32

that the borehole strainmeter sensors have only been approximately calibrated in terms of absolute strain amplitude, it will suffice for a demonstration of instrumental performance that the proper phase relationships exist between the observed strains and the theoretical tidal strains.

In the data comparisons which follow, we have utilized data from strain sensor H2A, oriented at an aximuth of 137°, because this sensor was operated at the highest sensitivity of all the strain sensors. Recordings from this sensor were made at a sensitivity of 8×10^{-10} per millimeter of chart defelction (full span of 2×10^{-7}).

The strainmeter record for sensor H2A beginning at 23 hr 30 min 00s on 1 March 1974 and ending on 25 March 1974 is shown in Figure 32. The direction of compression on the strain record is upward. Hourly amplitude readings were taken manually from the original strain records and major strain offsets and strain drifts caused by the grout curing process were graphically removed. The resulting analog record shows earth tides clearly.

A comparison between the observed and theoretical tides for a 5-day segment of strainmeter data in March 1974 is shown in Figure 33. Extension is upward on the record. The observed strain amplitudes for sensor H2A are about 40% smaller than the theoretically predicted amplitudes but the comparison in phase is very good, demonstrating that the strain sensor is indeed responding to the tidally induced strains. Perfect amplitude agreement is not to be expected in view of the uncertainties in h and ℓ, the magnitude of the ocean loading effect, the complex geologic structure of the Mina, Nevada site and the incomplete analysis of strainmeter calibration. A more rigorous analysis of amplitudes could be achieved by a detailed comparison with the long baseline components in the tunnel and a theoretic l analysis of the borehole and instrument canister effects. However, there is general agreement with the peak-to-peak tidal amplitude of approximately 2×10^{-8} recorded by the University of Nevada long-baseline strainmeters (Priestly 1973).

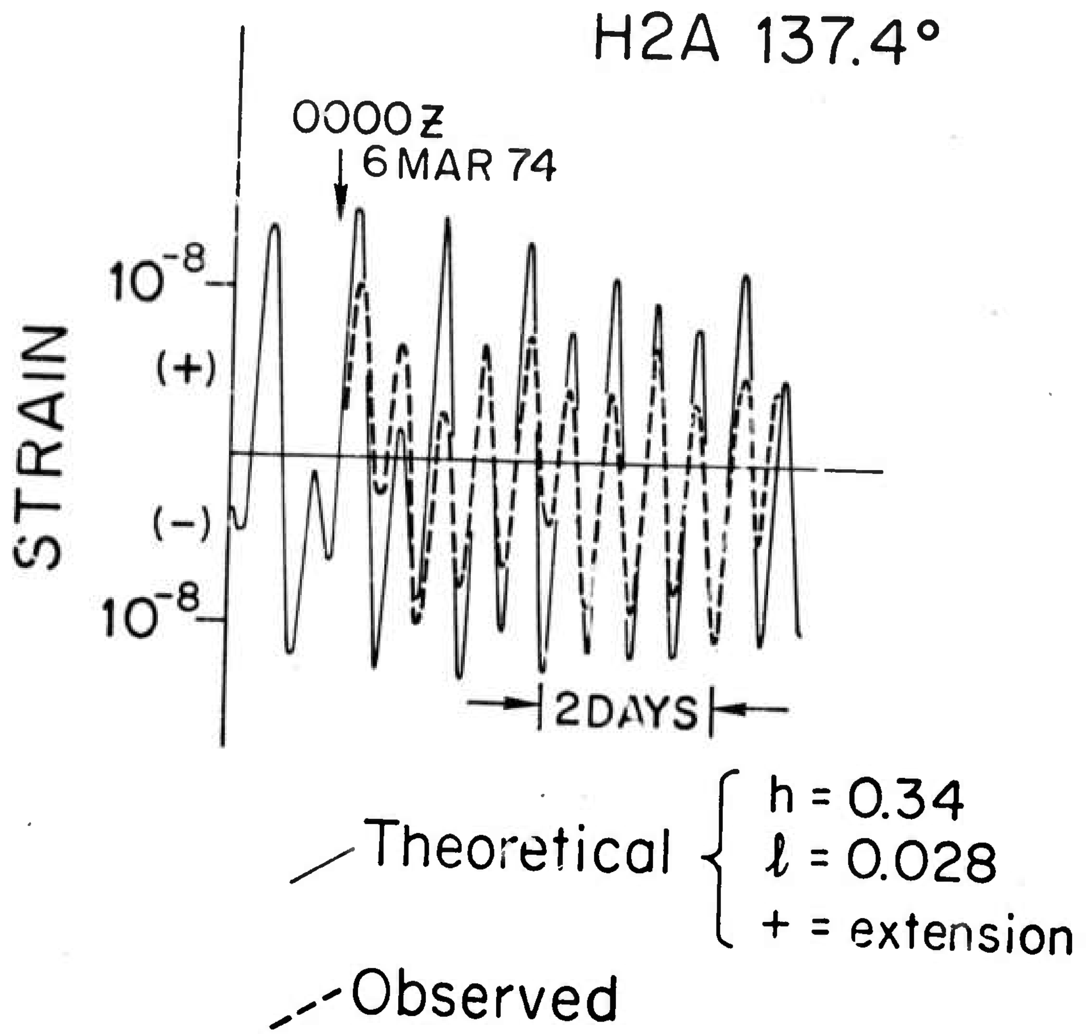

H2A 137.4°
0000Z
6 MAR 74
STRAIN
10^-8
(+)
(-)
10^-8
2DAYS
Theoretical
h = 0.34
ℓ = 0.028
+ = extension
Observed

FIGURE 33

A comparison of a 9.5-day segment of strainmeter in May 1974 for sensor H2A is shown in Figure 34. The data are in excellent phase agreement with the theoretical tides. Even though there is considerable drift over this time interval the amplitude modulation of the diurnal and semi-diurnal components by more long-period tidal constituents can be seen.

The borehole strainmeter design also provided for a vertical strain sensor. Figure 35 shown a comparison of the vertical component strain data (VA) with the H2A horizontal component strain data for an 8-day interval in February 1974. The H2A sensor was operated at a full-scale sensitivity of 2×10^{-7} whereas the vertical sensor was operated at a sensitivity of 1×10^{-7}. Observe that the amplitude of the peak-to-peak strains for the vertical component is approximately 1×10^{-9} compared to approximately 1×10^{-8} for the horizontal component. On this figure the direction of compression is upward. The phase relation between the H2A sensor and the VA sensor is clearly shown in that compression of the strainmeter canister should produce extension on the vertical sensor. This observed phase relation is also in agreement with theoretical considerations which shows that the vertical strain is proportional, but out of phase, with the areal strain

$$e_{rr} = - \frac{1}{3} (e_{\theta\theta} + e_{\lambda\lambda})$$

(It is assumed that the Lamé elastic coefficients are equal.)

At the present time we have demonstrated that the borehole strainmeter is indeed responding to tidal strains. The slow decay of the observed strain drifts at the Mina installation are undoubtedly related to the curing of the concrete which surrounds the strainmeter canister and other complexities due to the tunnel installation. There is no way to estimate the duration of this effect so we are unable at this time to estimate the long-term stability of the borehole strainmeter and its potential for measuring secular strain.

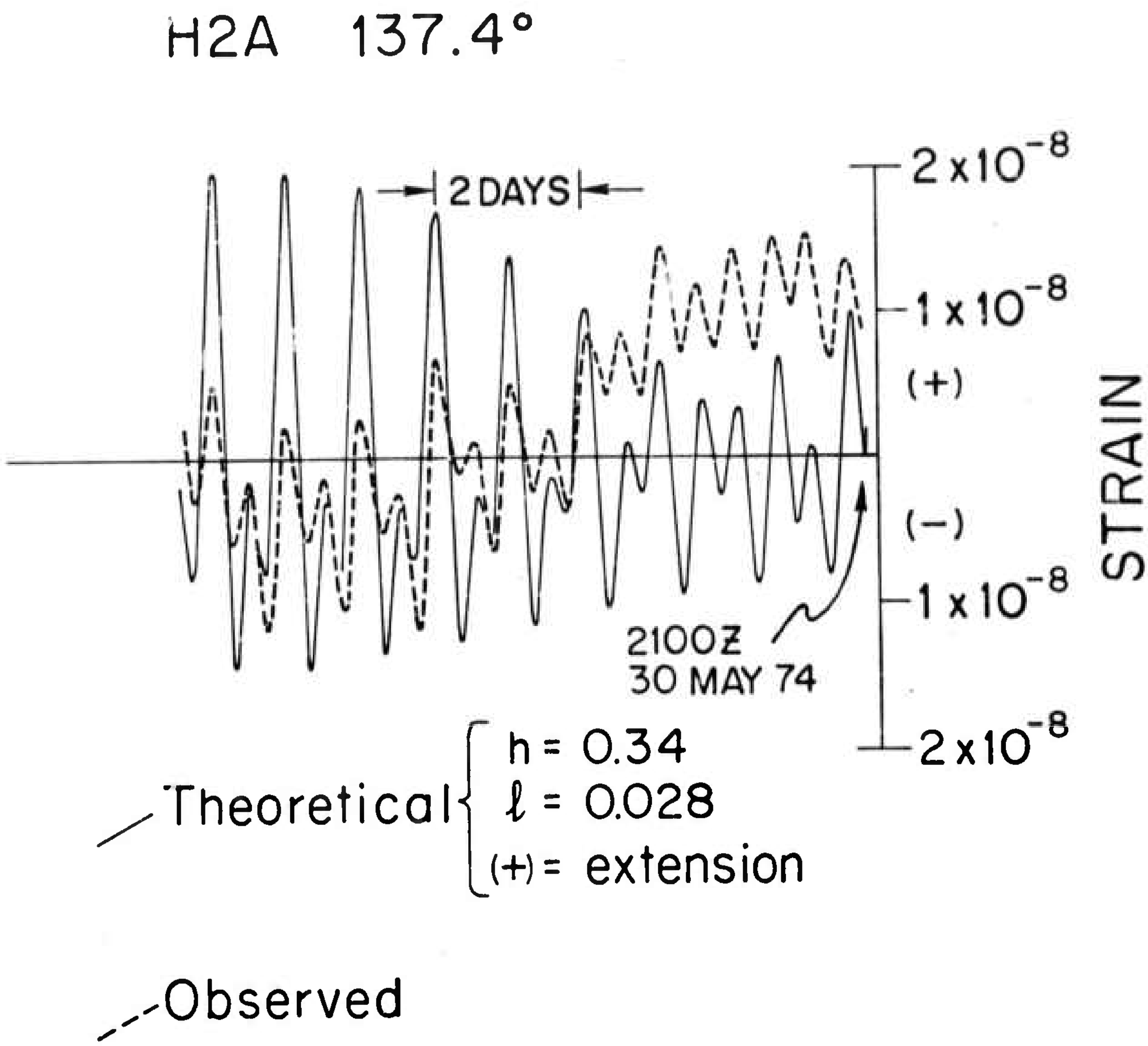

H2A 137.4°
2 DAYS
2 x10^-8
1 x 10^-8
(+)
(–)
1 x 10^-8
2 x10^-8
STRAIN
2100Z
30 MAY 74
Theoretical
h = 0.34
ℓ = 0.028
(+) = extension
Observed

FIGURE 34

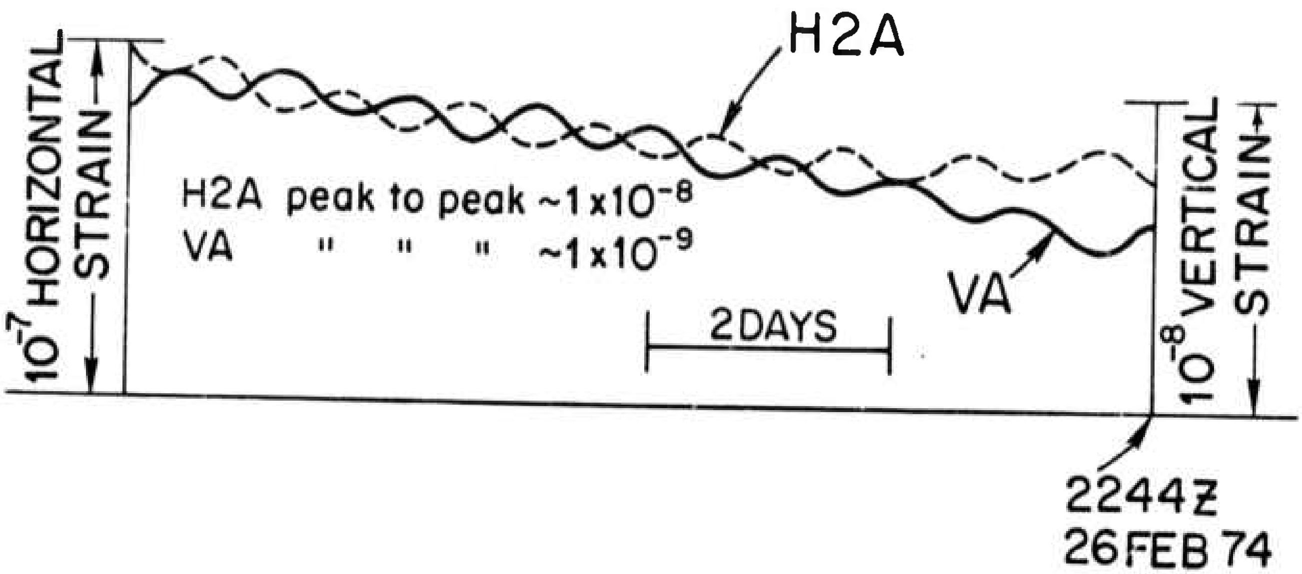

H2A
H2A peak to peak ~1x10-8
VA " " " ~1x10-9
VA
2DAYS
10-7 HORIZONTAL STRAIN
10-8 VERTICAL STRAIN
2244Z
26FEB 74

FIGURE 35

5. CONCLUSIONS AND RECOMMENDATIONS

A shallow-hole version of the borehole strainmeter was installed in a mine tunnel at Mina, Nevada, which contains University of Nevada long-baseline strainmeters. The installation is located in a seismically active area. The tunnel has adequate overburden and is baffled to provide the good thermal stability required to evaluate strainmeter performance at a significant depth below the surface without the additional mechanical complexity that would be required for an actual deep borehole installation. The slow decay of strain drift caused by curing of the grout surrounding the strainmeter canister continues to progress, but it has not yet reached a small enough level to estimate, at this time, the ultimate long-term stability of the instrument or its potential for measuring secular strain. However, it has clearly been demonstrated that the strainmeter is responding to tidal strains with an amplitude of approximately 1×10^{-8} in the horizontal direction and approximately 1×10^{-9} in the vertical direction.

Now that the means of making measurements of earth strain in borehole installations has been realized, it may be possible to resolve a number of important questions in the future. Measurements with conventional strainmeters have suggested that some large underground explosions and fluid injection operations appear to cause a regional adjustment in the earth strain field whereas others do not. Earthquakes also cause strain changes, but the data taken are widely divergent depending on the location of the recording site and the region in which the earthquake occurred. Recent work has suggested that dilatancy of rocks under stress prior to an earthquake may be a precursor to an impending event. The borehole strainmeter, therefore, is a potential tool for obtaining fundamental answers on the correlation of strain and events as part of the continuing studies of fluid injection and explosion effects evaluation. Furthermore, it is possible to make strain measurements in holes strategically placed along active fault zones and examine if indeed dilatancy is occurring prior to an earthquake. This makes the borehole strainmeter a potentially useful tool for earthquake prediction and control studies.

Among the locations that could be considered for future deep-hole installations are the AEC's Nevada Test Site, existing strainmeter sites in California and Nevada, various oil and geothermal fields and the San Andreas fault. The Nevada Test Site has obvious potential for correlating the effects of large underground explosions, earthquakes and strain changes. Oil and geothermal fields pose problems of unpredictable tectonic effects and geological uncertainty so they are felt to be a bad risk for a first installation. However, the potential environmental problems caused by fluid injection to recover oil and the exploitation of steam and hot water suggest important work for the future in these areas. An exploratory 2000-foot borehole exists at Stone Canyon, near the San Andreas Fault south of San Francisco, California, which is now being used for earthquake investigations.

To achieve suitable results, the site at which the borehole is drilled should meet certain requirements. First, the strainmeter should be emplaced in crystalline rock in order to achieve reproducible strain measurements. A second reason for choosing a deep hard rock stratum is to insure that temperature variations from natural sources, such as hydrological conditions, are small. Variations greater than a few millidegrees celsius may introduce first-order strain errors which must be decalibrated with an attendant reduction in accuracy. (Since the strainmeter is grouted in place, borehole circulation which might introduce temperature variation is prevented.) The third principal requirement is to install the instrument at a depth where other surface effects, such as wind or temperature-induced stresses, are sufficiently attenuated. An area with a low surface roughness coefficient is preferred since the installation can be made at shallower depths. The precise depth required for a suitable installation is uncertain. A depth as shallow as 1000 feet could be safe in terms of meeting scientific objectives, depending on the geological characteristics at the location. Since all fractures probably will not be closed at depths shallower than 10,000 feet, a test hole and geophysical logs would be required to determine the precise depth that is geologically suitable. The predominant surface effects will probably be wind loading and surface heating which require

theoretical calculation of their effect on the mean amplitude of surrounding terrain to determine the depth at which they are sufficiently attenuated. It is believed that a depth of 2000 feet is adequate for many situations and this figure should be used for planning purposes. Further, location in a well-monitored, seismically active area is desirable to aid in assessing instrument performance and interpreting the strain data. Frequent seismic activity resulting in transient elastic strains within the range of the strainmeter (10^{-9} to 10^{-5} strain) is optimum.

The important conclusion is that deep-hole strainmeter installations are feasible and meaningful strain measurements can be made over very short baselines. It has been demonstrated that multi-axis borehole strainmeters can be constructed with sufficient sensitivity to respond to earth tides as demonstrated by a shallowhole installation, in spite of environmental limitations in the mine tunnel. We believe that ability alone may make the borehole strainmeter a useful tool for pre-earthquake dilatancy studies. Although the slow curing of the grout, power outages, and possible fractured rock effects have precluded a final estimate of the instrument's long-term stability, and thus its potential for measuring secular strain, there does not appear to be any fundamental reason why sufficient stability cannot be achieved. In addition, practical installation methods have been defined which appear optimum in providing a high probability of success for minimum cost at depths of several thousands of feet. Future efforts to continue the evaluation and application of this device are therefore recommended in the following areas:

- Continue operation of the shallow-hole strainmeter over a significant period of time to suitably analyze instrument, grout and surface (tunnel) effects using advanced data analysis techniques to compare the borehole sensor components to each other and the long-baseline strainmeters in the tunnel.

- Conduct a more rigorous analysis of the effect of the borehole and instrument canister on measured amplitudes.

- Modify the grout formulation to achieve a mixture which stabilizes more quickly without significant degradation of handling characteristics.

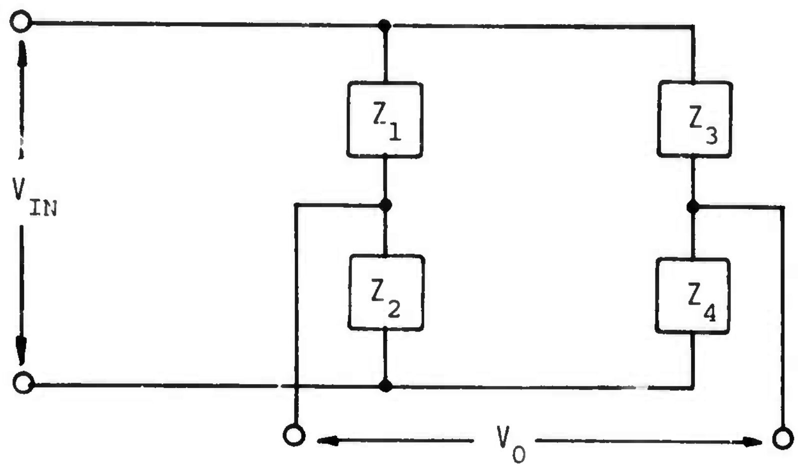
- Construct a strainmeter which includes the pressure equalization design options and install in an existing intermediate depth borehole for the purpose of investigating the correlation of earthquakes and strain field behavior at significant depths below the surface.

APPENDIX A

DERIVATION OF BRIDGE VOLTAGE MAGNIFICATION

DERIVATION OF BRIDGE VOLTAGE MAGNIFICATION

The bridge equivalent circuit is



where $Z = \frac{d}{\omega A \varepsilon}$ and $\frac{1}{\omega A \varepsilon} \equiv k$, $\omega = 2\pi \times$ frequency, A = capacitance plate area, and d = capacitance plate spacing.

Assume a small sensor movement of Δd as follows:

Z_1 goes +	then: $Z_1 = k(d + \Delta d)$
Z_2 goes -	$Z_2 = k(d - \Delta d)$
Z_3 goes -	$Z_3 = k(d - \Delta d)$
Z_4 goes +	$Z_4 = k(d + \Delta d)$

therefore: $Z_1 = Z_4$ and $Z_2 = Z_3$.

The output voltage is

$$V_0 = \left(\frac{V_{IN}}{2} - \frac{V_{IN} Z_2}{Z_1 + Z_2}\right) + \left(\frac{V_{IN} Z_4}{Z_3 + Z_4} - \frac{V_{IN}}{2}\right)$$

$$= V_{IN}\left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)$$

$$= V_{IN}\left[\frac{k(d + \Delta d) - k(d - \Delta d)}{K(d + \Delta d) + k(d - \Delta d)}\right]$$

$$= V_{IN}\left(\frac{\Delta d}{d}\right).$$

The sensor movement Δd is related to rock strain as follows

$$\Delta d = K\,D \cdot (\text{strain})$$

where K = the magnification of strain by the borehole (horizontal sensors only. The baseline of the vertical sensors is increased to provide an output identical to the horizontal sensors for a given strain.)

D = the strain sensor baseline.

therefore:

$$V_O = V_{IN}\left[\frac{K\,D\,(\text{strain})}{d}\right]$$

Assume K = 1.5, D = 6 inches, and d = 6 x 10^{-3} inches, then

$$V_O = V_{IN}\left[\frac{(1.5)(6)}{6 \times 10^{-3}}\,(\text{strain})\right]$$

$$= V_{IN}\left[1.5 \times 10^{3}\,(\text{strain})\right]$$

APPENDIX B

SUMMARY REPORT ON LABORATORY DEVELOPMENT
AND
FIELD PLACEMENT OF GROUT FOR THE BOREHOLE STRAINMETER

Summary Report on
Laboratory Development and Field
Placement of Grout for the Borehole Strain Meter

Summary

1. The development of a coupling grout exhibiting the necessary characteristics for emplacement of the deep borehole strain meter was accomplished by the Concrete Laboratory of the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. Slight expansion (approximately 1 part/thousand) was desired initially for positive coupling. This was done by using a small quantity of expansive cement. A major requirement was the long-term stability, desirably 10^{-8}/day, as soon as possible following placement.

2. Several formulations were investigated containing cement, fly ash, gels, etc., in varying proportions. Dimensional changes were monitored for selecting the mixture exhibiting the greatest stability as projected to later ages. Tests over a six-month period indicated the mixture to meet the criteria. The mixture was then tested to determine the temperature and pressure dependence of both the initial expansion and the final long-term stability. These influences were insignificant. While the experimental program became quite involved to simulate stable pressures and temperatures as found in-situ, the results indicated a coupling grout for use in deep holes stable to at least 0.11 parts/million/day at the end of a one-year test period.

3. Grout materials and proportions used for the grout developed for use in coupling the borehole strain meter were as follows:

Material	Bulk Specific Gravity	Weight and Volume for 1-cu-ft Yield		
		Unit Wt Solid lb/cu ft	Solid Vol cu ft	SSD Wt lb
Cement "II"	3.15	196.25	0.224	43.82
ChemStress II	3.08	191.88	0.001	0.17
Fly Ash	2.45	152.64	0.183	27.99
Gel	2.39	148.90	0.014	2.16
CFR-2	--	--	--	0.29
Water	1.00	62.3	0.578	35.99

Theoretical unit weight, lb/cu ft:	110.1
Theoretical cement factor, b/cu yd:	12.6
Water-cement ratio by weight:	0.5
Fluidity, flow cone, seconds:	12.3
Initial setting time, hours:	8-9
Final setting time, hours:	11-12

Strength Test Results

Shear bond at 28 days age (sandblasted surface):	605 psi
Shear bond at 28 days age (machine grooved):	725 psi
Unconfined compressive strength at 28 days age:	3980 psi

Drop Tests for Workability Time

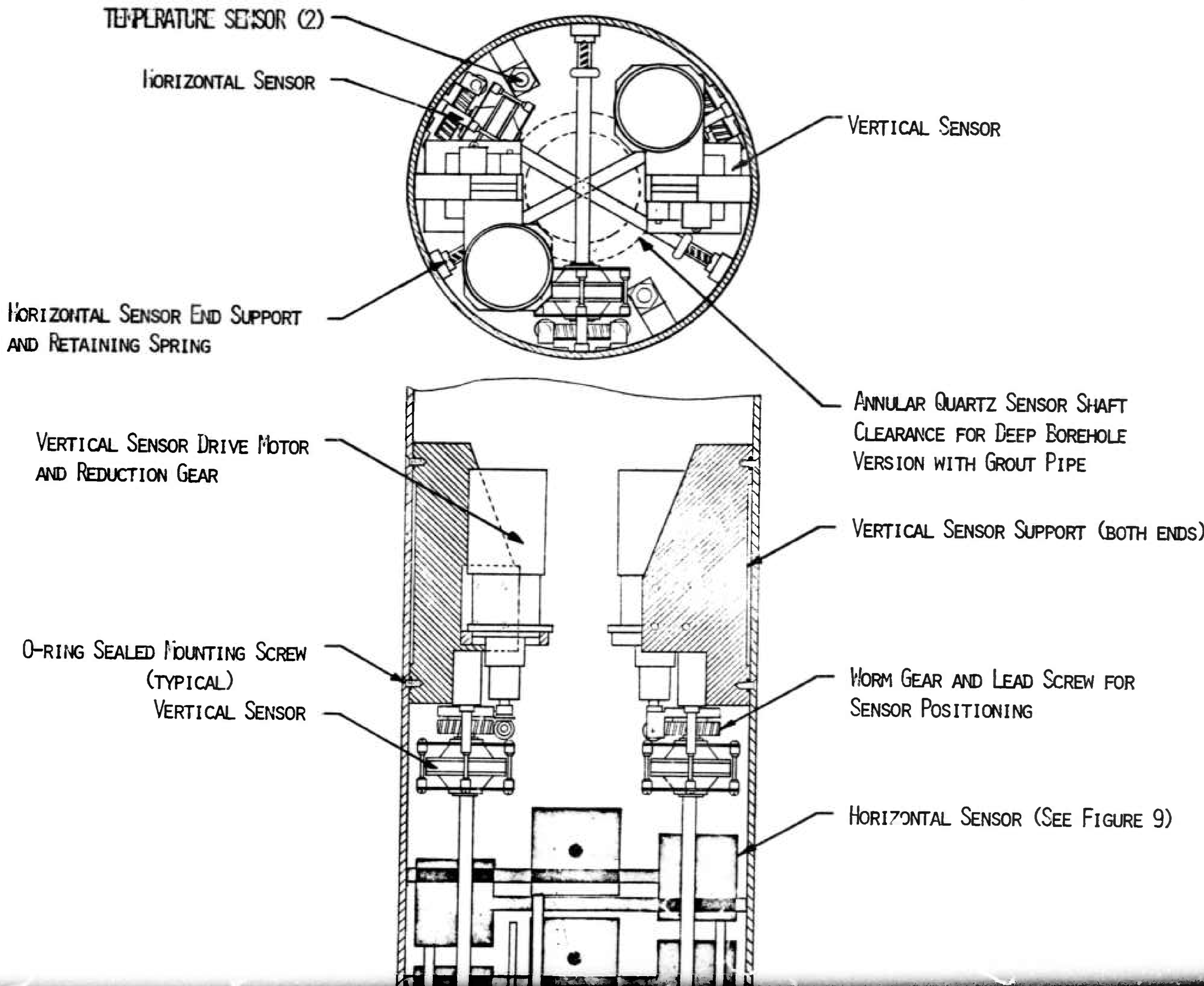
Time	Temperature, F	Results
0900	Oven 100	--
0905	Grout 80	Placement temperature.
1105	Grout 92	Tube removed with ease.
1155	Grout 93	Tube removed with some difficulty.
1235	Grout 95	Tube removed with much difficulty.

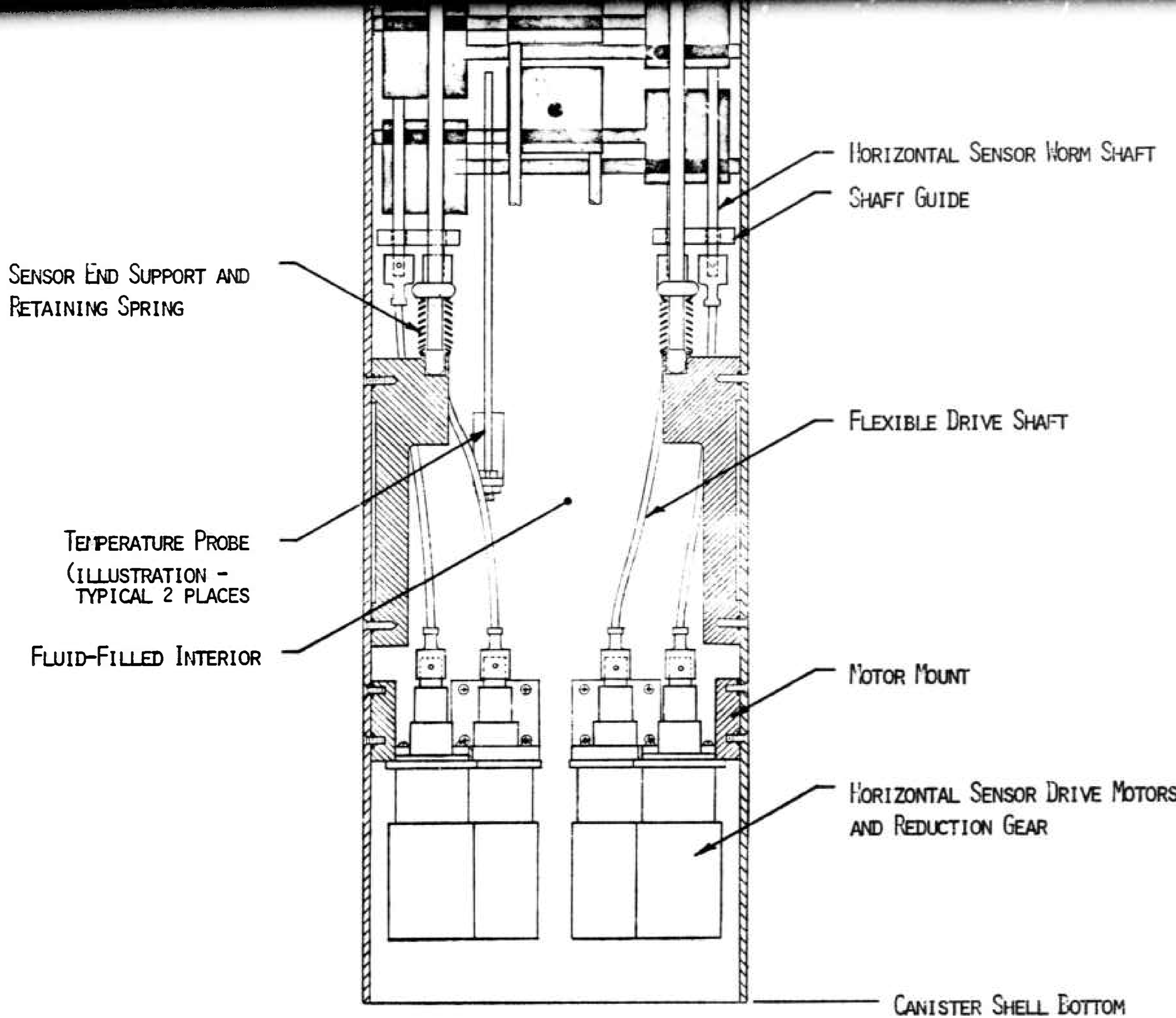
Field Emplacement of Grout

4. Mixing of the grout was conducted near the tunnel portal in quantities of 1 cu ft/batch. The freshly mixed grout was hand-carried by means of 5-gallon buckets into the tunnel. At the time of placement, the grout temperature was measured to be 50 F, and the tunnel ambient temperature was approximately 40 F. The grout was slowly introduced into the hole containing the strain meter by means of a funnel. Approximately 1 cu ft of grout was required to fill the hole over a period of approximately 1-1/2 hours. On the following morning, the surface of the grout was examined. It had developed a hard set and exhibited no evidence of surface cracking or shrinkage.

APPENDIX C

DETAIL OF SENSORS MOUNTED IN CANISTER


TEMPERATURE SENSOR (2)
HORIZONTAL SENSOR
VERTICAL SENSOR
HORIZONTAL SENSOR END SUPPORT AND RETAINING SPRING
ANNULAR QUARTZ SENSOR SHAFT CLEARANCE FOR DEEP BOREHOLE VERSION WITH GROUT PIPE
VERTICAL SENSOR DRIVE MOTOR AND REDUCTION GEAR
VERTICAL SENSOR SUPPORT (BOTH ENDS)
O-RING SEALED MOUNTING SCREW (TYPICAL)
VERTICAL SENSOR
WORM GEAR AND LEAD SCREW FOR SENSOR POSITIONING
HORIZONTAL SENSOR (SEE FIGURE 9)



SENSOR AND MOTOR MOUNTING
(INTERMEDIATE AND SHALLOW DEPTH VERSION ILLUSTRATED)